State of Washington Water Research Center
Annual Technical Report
FY 2017

Introduction

Report Introduction

Like most Western States today, The State of Washington faces substantial water resource challenges. Recently the state had one of the worst droughts of the century, exacerbated by a warm winter and low snowpack throughout the Cascades. The Columbia River Treaty of 1964 between the U.S. and Canada is being considered for renegotiation, and legal and surface-groundwater interactions and conjunctive use are center stage in legal and policy developments regarding instream flows, Native American Treaty rights, and residential and municipal groundwater development. Proposals for more surface and aquifer storage and recovery continue to be introduced, while water market infrastructure continues to develop across the state to facilitate water transfers. Water quality issues relating to stormwater runoff into the Puget Sound and concentrated livestock production east of the Cascade are holding the attention of both the courts and the State Legislature. All of these issues and decisions require and can benefit from science-based research and outreach from water research and management professionals across the state. The State of Washington Water Research Center is working to position itself to be a critical provider and coordinator of these science-based research and information needs.

The State of Washington Water Research Center continues to engage the scientific community, the public sector, and water resource stakeholders at large to address these challenges and improve water resource management throughout the state and region.

Mission statement

In the spirit of the WRRA of 1964, the mission of the State of Washington Water Research Center (WRC) has three components: 1. To conduct and facilitate applied water-related research. 2. To foster education and training of future water professionals. 3. To serve as a nexus between the academic community, water resource managers and water stakeholders. These three elements of the WRC mission are the fundamental goals supporting the WRC vision, objectives, strategies, and assessment metrics described in this Strategic Plan.

Vision statement

The current WRC administration envisions strengthen WRC impact through the following activities:

1) Actively engaging water research professionals at other academic institutions to encourage their participation in the administration and activities of the WRC, 2) Developing broader collaborations among water researchers within WSU and between WSU and other water-focused organizations. 3) Increasing programmatic and extramural funding to support the WRC and its activities. 4) Developing more focused and integrated water resource education programs at WSU. 5) Creating a wider network for outreach, and contribute more broadly to information dissemination for water stakeholders and policymakers.

Guiding principles

The mission and vision of the WRC will be guided according to the following principles:

1) WRC will focus on and facilitate integrative research and education throughout all core water-related programs. At the heart of modern integrative water research is a need for interdisciplinary collaboration. 2) WRC will endeavor to complement rather than duplicate the efforts and missions of other water-focused centers both within WSU and across other state and regional organizations. 3) WRC will continue and strengthen its direct involvement in water-related research, but will also strengthen its indirect contributions to

impactful water research by increasing the level of support and incentives provided to prospective researchers in the form of administrative support, information provision, focus and guidance, and direct facilitation of and collaboration in research and academic pursuits. 4) WRC will maintain and strengthen its reputation as an independent and neutral provider of reputable science and policy research.

Current Administrative Staff and advisory committees

The WRC staff includes a Director (0.5 FTE), and Associate Director (0.25 FTE), a Clinical Assistant Professor (0.5 FTE), a Principal Assistant (0.5 FTE), and a Grant and Contract Coordinator (.375 FTE). In addition, the WRC has two advisory committees: a set of Program Directors, and a Science Advisory Committee. These positions and committees are currently filled by the following people:

- **Center Director** Jonathan Yoder (Director)
- **Faculty and Staff** Julie Padowski (Clinical Assistant Professor) Jacqueline McCabe (Principal Assistant) Katrina Shelton (Grants & Contracts)

In addition, the WRC has three advisory committees: a set of 3 Program Directors, 4 WRC Campus Representatives and a Science Advisory Committee comprising 11 individuals from throughout the state and with varying expertise. The Science advisory committee provides guidance about the research emphasis of the WRC, and is the review panel for the 104(b) grant applications. es: a set of 3 Program Directors, 4 WRC Campus Representatives and a Science Advisory Committee comprising 11 individuals from throughout the state and with varying expertise. The Science advisory committee provides guidance about the research emphasis of the WRC, and is the review panel for the 104(b) grant applications.

Administrative activities

Grant management and planning

In addition to the USGS WRRA 104(b) grant program, the WRC is administering three extramural grants and has been both following through with past grant research and pursuing other opportunities through grant proposal submission and planning. The Hanford Groundwater research project ($40,000) Director Yoder is the lead Investigator with Julie Padowski and Nigel Pickering as Co-PI¡¦s. The Forecast: State Caucus ($40,000). Jennifer Adam is the lead Investigator with Jonathan Yoder as Co-PI. Defining Net Ecological Benefit for implementation (initial phase preparation funding $4,046). Director Yoder is the lead Investigator with Jennifer Adam, Michael Brady, Joseph Cook, Stephen Katz, and Julie Padowski as CO-PI¡¦s.

Collaboration building within WSU and beyond

The WRC continues to expand its collaborative network within WSU and the State of Washington. With the hiring of our water quality and stormwater expert, we are building stronger ties with the WSU Stormwater Center. Because WSU water researchers are scattered across several campuses, we are examining the possibility of adding a WSU Water Program Coordinator to help facilitate collaboration among faculty across campuses.

The WRC currently has two primary connections to State government at the Washington State Department of Ecology, and the State Legislature. The Department of Ecology has been the source of a substantial share of WRC extramural funding in recent years to support WRC research to provide long-run water supply and demand forecasts for the State of Washington, which the Ecology Office of Columbia River oversees on a five-year cycle. The WRC is also currently building stronger ties to the Ecology Water Resource Program, which oversees a broader array of water resource and regulatory issues. The State legislature has over the last several years identified the WRC as a source of independent research on water-related issues.

In addition, we are strengthening our collaborations with Pacific Northwest National Laboratories and the USGS Washington Water Science Center through building a more robust student internship conduit to these organizations. We have collaborated with the WSU academic administration to establish an undergraduate interdisciplinary water science and management certificate, which is the first coordinated interdisciplinary water program at WSU.

The WRC administration intends to continue fostering its role as an independent source of quality research to help address the State of Washington¡¦s needs. The WRC administration is in communication with the WSU office of State relations to begin to explore ways of securing additional state base funding to support personnel for actively, permanent outreach and research programs.

Research Program Introduction

Research Introduction

WRC's research program is active along several dimensions. First, the WRC manages a seed grant program funded by the Water Resources Research Act (WRRA) 104(b) funds. Second, it is currently managing three extramural grants to support research and has two more that have been awarded with the funds pending. Third, it has submitted and has begun preparing several proposals this past year for additional funding. Finally, it is pursuing a broad strategy for developing and strengthening research funding opportunities and collaborative opportunities within and outside of WSU and the State of Washington.

2018 WRRA 104(b) Seed Grant program: The WRC funded two small water-related grants ($27,500/grant) under the WRRA 104(b) FY2018 grant program. These projects are currently under way.

Washington wildfires disrupt water quality: Are drinking water systems resilient to climate change? Amanda Hohner and Jan Boll; Assistant Professor and Professor, Washington State University. Project #2018WA434B.

Understanding controls on mobility and toxicity of tungsten, an emerging threat to Washington's waters. Nikolay Strigul and John Harrison; Assistant Professor and Associate Professor, Washington State University. Project #2018WA438B.

WRRA 104(b) Seed Grant program reports: 2017 and prior

Post-contract reports are required for all 104(b) seed grants. References for the reports submitted in 2017 for the FY2016 are provided in the bibliography Appendix A.

2017 WRRA 104(b) Seed Grant program:

Scaling of hydrologic and land-surface responses: Are the right processes represented at the right scale? Nicholas Engdahl and Alexandra S. Richey; Assistant Professor and Research Associate, Washington State University. Project #2017WA425B.

Adaptive governance of riparian lands in Washington State: coordinating policy and practice to leverage river and floodplain benefits. Alexander K. Fremier and Barbara Cosens; Associate Professor, Washington State University and Professor, University of Idaho College of Law. Project #2017WA428B.

Frequency Analysis of Historic and Future Droughts in Yakima Basin. Yonas Demissie, Jennifer Adam and Akram Hossain: Assistant Professor, Associate Director, and Professor, Washington State University. Project #2017WA429B.

Extramural grant-funded research

Hanford Groundwater Research Project. This study is funded by the Washington State Department of Ecology. Awarded 5/2017 ($40,000).

Forecast: State Caucus. Funded by the Washington State Department of Ecology. Awarded 7/2017. ($40,000).

Irrigation Depletion Methodology Development. This study was awarded by DOE-BPA. Submitted 1/2018, fund pending. ($135,038)

Water Markets for the Yakima Basin: Researching and Developing Strategies for Multi-Benefit Markets. Awarded by Trout Unlimited 11/2018 ($48,250).

Grant development activities

The Administrative team continues to pursuing further extramural support in line with the WRC strategic plan. It was a major contributor to a proposal submission to the USDA AFRI CAP Water for Agriculture program, with a request for joint effort between WRC, CEREO, CSANR, and the School of the Environment ($10 million) submitted through CSANR. WRC is taking the lead on another of these grant proposals this year. In addition, members of the WRC administration are involved in an awarded NSF INFEWS proposals beginning this year ($3,000,000)

More generally, the WRC has been positioning itself for future research funding and collaborative opportunities. Some of these activities are described above.

Education

The WRC has developed and implemented a Certificate in Water Sciences and Management for undergraduate and graduate students at WSU. In an effort to be sensitive to other department's course development and to most effectively use the existing water-related curriculum, we identified a core curriculum of existing WSU water-related courses. These courses are grouped into several major themes a student can pursue, for example Riparian/aquatic ecology, Water management and policy, Water Quality, Groundwater, and Surface Water. Certificate requirements will be consistent with WSU guidelines. In addition to a Certificate, the WRC is also reviewing different strategies for implementing a floating interdisciplinary graduate program. Several universities have successful examples of these types of programs.

Scaling of hydrologic and land-surface responses: Are the right processes represented at the right scale?

Basic Information

Title:	Scaling of hydrologic and land-surface responses: Are the right processes represented at the right scale?
Project Number:	2017WA425B
Start Date:	3/1/2017
End Date:	5/31/2018
Funding Source:	104B
Congressional District:	WA-5
Research Category:	Ground-water Flow and Transport
Focus Categories:	Hydrology, Groundwater, Management and Planning
Descriptors:	None
Principal Investigators:	Nicholas Engdahl, Alexandra S Richey

Publications

There are no publications.

Progress report for “Scaling of hydrologic and land-surface responses: Are the right processes represented at the right scale?”

N.B. Engdahl and A.S. Richey

1. Overview

Groundwater is declining across much of Washington State [*Burns et al*., 2012; *Vaccaro et al.*, 2015] and there is a general consensus that climate change will place significantly more stress on existing resources [*Pitz, 2016*]. The Washington State Department of Ecology (Ecology) has called for establishing formal mechanisms to monitor and assess current and future groundwater depletion in the state’s aquifers [*Pitz*, 2016], which will require an exhaustive inventory of existing resources as well as dynamic models to infer future changes. This is problematic because there is a discrepancy between the scale of hydrologic measurements, often scattered points, and the scale of management decisions across the entirety of a region. Long-term planning and management typically involves combining observations with modeling, so the disparity of the information sources could lead to large discrepancies between planned usage and actual usage, making the problem very real. As such, the central theme of this project is the transfer of information across scales and whether or not a model constructed at one scale (resolution) is equivalent to another model constructed at a different scale over the same area.

Data interpolation and numerical modeling efforts are often combined to coarsen local measurements for regional applications but doing so confidently requires an understanding of how hydrologic processes interact across scales. The average response of a fine resolution model for total water content, for example, may not match the result of a coarse resolution model even when they are calibrated to the same data [*Hill and Tiedeman*, 2007]. The reason for this phenomenon is twofold, with part of it being the mathematical issue of non-uniqueness and the other being the nonlinear response of the complex processes. The former is unavoidable, but the latter occurs because the numerical solution (integration) of the governing equations changes when solved at different scales. The main goal of the project is understanding how these kinds of disparities affect the results of groundwater models. Specifically, we ask, how do process interactions and the hydrological response at small scales translate to larger scales? The reason this question is so critical is that, overwhelmingly, the only comparison metrics for hydrologic simulations are point observations (heads, streamflow, volumetric water content, etc…), and if two models of the same site can be fit to the same data equally well, how can one say which is correct? The approach for investigating these questions is to use multi-scale numerical models to quantify the magnitude and spatial trends in the differences seen at the different scales for the same sites. We have made significant progress toward understanding how the nonlinear response of these hydrologic systems differ and are nearing completion of the project.

1.1 Study sites

The project originally intended to use the Cook Agronomy Farm (CAF) located near Pullman, WA which is managed by Washington State University (WSU) in collaboration with Pullman USDA/ARS scientists (http://css.wsu.edu/cook/). The CAF (Figure 1) is part of the Long-Term Agroecological Reserve (LTAR) network established by the U.S. Department of Agriculture and the site covers an area of roughly $0.57 km^2$, spanning an area several hundred meters across. The CAF is home to a large number of multi-disciplinary research projects focusing on agricultural efficiency and process-oriented applied research. Based on conversations with colleagues who have worked at the site, we were led to believe that the abundant data (both characterization and observation) was readily available. However, this was found not to be the case. Apparently, despite numerous persons believing otherwise, no central data repository for the site exists. The limited data sets we could obtain were not detailed enough and everyone involved with this data “thought” someone else had more of it. Clearly, sorting out these discrepancies is an issue for the CAF team, not ours, and accordingly we sought alternatives to circumvent the lack of data availability.

Our alternative was to use two sites, one synthetic to eliminate uncertainty and the other based on a real watershed that does have observation data. The synthetic domain is a common geometry used in testing hydrologic models referred to as a 3-D Tilted-V watershed. This simple domain has an analytically defined geometry (surface slopes) and uniform hydrologic parameters within three analytically defined regions, meaning that “exactly equivalent” versions of the problem can be constructed at any grid resolution. By exactly equivalent, we mean that no resampling or averaging of parameters is needed, so a model with 10m by 10m cells should have precisely the same output as one constructed with twice as many 5m by 5m cells if there are no grid effects or nonlinear scaling effects. The second site we selected is the Dry Creek Experimental Watershed (DCEW) North of Boise, ID. This location has a climate similar to the Palouse and the monitoring data for the site is openly maintained on a public website. The data includes hydrologic (streamflow and soil moisture) and meteorological data (precipitation, temperature). The site is roughly 36km^2 and has a combination of grassy and forested slopes, with variable slope angles, and good characterization of the soils in the upper 2m of the watershed. Overall, the data at DCEW has the level of support and confidence that typically leads to an accurate integrated model of a site. Conceptually, the synthetic domain is similar to CAF but DCEW is fundamentally different from CAF because it is larger, steeper, and forested instead of farmed. However, the interaction of slopes and vegetation with profoundly different water demands (grasses versus trees) is a more challenging, and broadly transferable, problem with which to test scaling laws and the synthetic domain retains many similarities to CAF.

2. Progress and Results

The PhD student supported by this project has made excellent progress in modeling the systems and analyzing the results. The simulations and analysis of the 3-D Tilted-V case are complete, and these mainly involved running the same benchmark problem for different computational grids and comparing their outputs. The simulations varied the spatial discretization laterally and vertically. The base-case scenario, which comprises the synthetic “true” result, used 1m by 1m cells laterally, and 0.1m think cells vertically. The lateral resolution was then changed 2m, 5m and 10m, respectively, and the simulations re-run. Vertical resolutions included 0.1m, 0.25m, 0.5m and 1m, but all models occupy the same domain volume. Each run used the same boundary conditions and the simulation represented a 12-hour rainstorm followed by a long period for it to drain off. We found that increasing the grid resolution increased the streamflow and also had significant impacts on other portions of the water budget. The largest compensatory effect was a decrease in the volume of saturated groundwater in the system, which was accompanied by small shifts in variably saturated soil moisture. We also observed significant changes in the spatial patterns of overland flow and soil moisture, where larger areas were inundated with surface water in the coarse grid simulations after the storm passed. Presently, the project student is proposing and developing scaling laws to describe these trends (*i.e.* an exponential relationship between streamflow and grid size) and preparing the results for inclusion in a publication. These results were presented at an international conference in December and were well-received by the scientific community.

The second portion of the project is nearing completion. The study at DCEW involves a larger, more complex domain, which requires longer model runtimes, but it also has observation data to consider. A similar approach to exploring scaling behaviors is being used but we limit this to three lateral grid resolutions because of computational limitations. There are several tradeoffs to consider because the model must be calibrated to ensure reasonable reproduction of the data. Our approach is to adopt the finest resolution (20m laterally) as the "truth" and calibrate the model parameters to this scale. However, translating this information to the coarser scales (40m and 60m lateral cell resolution) can be done in several ways. One option is to average the values from the small model to the larger models and another is to independently calibrate each resolution to reproduce the data (the outflow hydrograph) as closely as possible. Since it is unclear which of these gives the fairest comparison, both are being evaluated. The parameter upscaling (averaging) is already complete and we have found that this produces large differences in the magnitude of streamflow, but a similar trend to the 3-D Tilted-V was observed where larger grids gave more surface flow. This result is promising because it suggests that some scaling behaviors related to grid selection may have general trends that describe them, even when the nature of the flow systems is drastically different. Presently, we are completing the multi-scale calibrations and once this is completed we will have all of the simulated data needed to complete the scaling analysis.

3. Remaining tasks and anticipated timeline

The only tasks remaining are to complete the multi-scale simulations at DCEW and to complete the scaling analysis with those results. These simulations are taking longer than expected due to: 1) longer-than expected runtimes of the 20m resolution integrated model, and 2) the difficult, and often unpredictable, transient calibration process. We chose to use a real, specific storm in late October of 2012 for the DCEW study and physically-based hydrologic models have a large number of parameters that interact in complex ways, so these kind of delays during calibration are not unusual, but they also cannot be reliably estimated ahead of time. Once these simulations are completed, the student will work up an analysis of scaling behaviors at DCEW similar to what she has already done for the 3-D Tilted-V, and then a correlation analysis of the trends observed at both sites. She will also propose scaling laws for upscaling or downscaling results from one grid resolution to others and quantify the anticipated variability of the simulations. As these results become available, she will continue to make progress on her manuscript describing these results, for which we anticipate an August 2018 submission date to the Journal of Hydrology. The simulations are currently running, almost around the clock, and we expect them to be completed within the next 3-weeks. We originally intended to directly simulate land-surface process in these simulations, but it became clear that doing so would add too much complexity too soon. These simulations will still be done as part of the PhD students dissertation work but there was insufficient time for them to be considered in this project. Regardless, with further independent testing by other researchers, we expect that the scaling laws we are proposing may be able to provide the most reliable method for describing the range of variability one should expect from a calibrated model run at one scale relative to other scales. These relationships are already showing great promise in their resilience across domains that vary drastically in complexity, so we expect that similar scaling laws will be discovered when land-surface processes are included in the future.

Adaptive governance of riparian lands in Washington State: coordinating policy and practice to leverage river and floodplain benefits

Basic Information

Title:	Adaptive governance of riparian lands in Washington State: coordinating policy and practice to leverage river and floodplain benefits
Project Number:	2017WA428B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	5
Research Category:	Social Sciences
Focus Categories:	Ecology, Conservation, Management and Planning
Descriptors:	None
Principal Investigators:	Alexander K. Fremier, Barbara Cosens

Publications

1. Stahl, A.T., Fremier, A.K., and Cosens, B. Integrated legal-ecological landscape mapping identifies priority areas for habitat connectivity. Under review, Proc. Nat l. Acad. Sci.
2. Stahl, A.T., Fremier, A.K., and Cosens, B., 2018. Mapping legal authority for corridor conservation: local footholds for cross-boundary coordination. Submitted to Joint Regional Conference of the Society for Ecological Restoration Northwest Chapter and the Society of Wetland Scientists Pacific Northwest Chapter: Restoring Resilient Communities in Changing Landscapes, Spokane, WA.
3. Fremier, A.K., Stahl, A.T., and Cosens, B., 2017. Building ecological resilience through coordinated riparian conservation. The Wildlife Society Annual Conference, Albuquerque, NM.

Adaptive governance of riparian lands in Washington State: coordinating policy and practice to leverage river and floodplain protection benefits

State of Washington Water Research Center Seed grant #130985-001

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Abstract

Wildlife corridors are designed to mitigate habitat fragmentation, yet their success is often limited by political and economic barriers to building and maintaining them at the landscape scale. Although jurisdictional boundaries are considered in conservation planning, ecological connectivity models do not quantify spatially-explicit patterns in legal authority for corridor conservation. We formulated a method to map conservation authority across a county in Washington State (northwestern United States) and formalized an integrative legal-ecological corridor analysis to assess the potential contributions of the existing legal landscape to broader scale connectivity conservation strategies. The results show that incorporating the legal landscape into a connectivity model identifies different priority areas for rebuilding habitat connectivity than a model based on ecological conditions alone. Integrating legal authority with ecological corridor value across the landscape revealed social-ecological spatial patterns that enabled us to highlight areas of opportunity for promoting cross-boundary coordination, targeting areas for restoration, or effecting policy change to build and maintain habitat connectivity. This social-ecological categorization scheme is a step toward strategic corridor planning to address both social and ecological barriers to landscape connectivity.

Significance Statement

Demand is increasing for integrative social-ecological approaches to inform environmental management and conservation in the context of climate change and future uncertainty. Despite significant political and economic barriers to building and maintaining habitat corridors for wildlife conservation, habitat connectivity models do not yet explicitly, quantitatively incorporate crucial social aspects of landscape fragmentation. We formulated a method to evaluate the spatial arrangement of legal authority over a local landscape within the larger-scale ecological context of building habitat connectivity. The combined legal-ecological landscape revealed different priority areas for building habitat connectivity than those identified by ecological conditions alone. These results demonstrate one way in which social-ecological spatial analysis may offer new insights into persistent environmental problems.

Keywords

habitat corridors, jurisdictional mapping, legal authority, riparian, species conservation

Introduction

The overlay of climate change on landscapes fragmented by human activity threatens species' survival by limiting the ability to move to new habitats in response to environmental change (1). Accordingly, conservation efforts aim to promote species' survival by preserving or restoring habitat connectivity across landscapes (2). Nevertheless, corridor initiatives that require coordinated conservation efforts among stakeholders across large landscapes have been plagued with challenges (3). Current approaches to systematic, landscape-scale corridor conservation aim for species' persistence by mapping landscape condition and/or protected status (e.g., (4)). They generally lack an integrated legal-ecological framework for effective implementation. Progress toward such integration is hindered by the misalignment between jurisdiction and the spatial or temporal scales of ecosystem processes (e.g., species migration or flood buffering) (5).

Habitat corridors are designed to build connectivity for species conservation, focusing on a specified ecological level (individuals to populations) and scale (local to national) with goals relating to movement, dispersal, or long-term species persistence (2). Habitat connectivity models typically rely upon available spatial ecological data such as vegetative cover to inform corridor planning (6). They almost never codify and map the legal authority underpinning conservation planning (e.g., (7). Yet, pure ecological metrics may be neither timely nor sufficient for securing the long-term support of politicians and governmental officials that would be necessary to design, implement, and maintain habitat corridors (3). Moreover, species' movement in response to climate change raises complex issues that call for integrated ecological, conservation, and social research as well as engagement of the public and decision-makers (8).

Riverine corridors: leveraging ecosystem services for habitat connectivity

Given the degree of scientific uncertainty in models predicting future climate change and species' distributions, systematic conservation measures that aim for multiple positive outcomes may increase the likelihood of corridor success (9, 10). Corridor conservation would benefit from systematically building upon spatial overlaps between priority areas for ecosystem services and landscape-scale habitat connectivity. Incorporating multiple priorities into decision-making can be difficult, however, because it requires spatially-explicit consideration of the local setting within the context of broader-scale conservation issues (11). Information tools are needed to tailor and streamline this process.

We approach this problem by concentrating upon riparian ecosystems, the transition zones between rivers and adjacent uplands, as a potential nexus of ecosystem services and landscape-scale habitat connectivity (9). Riparian ecosystem services depend upon processes (e.g., nutrient filtration and flood attenuation) that are strongly linked to hydrology, climate, and adjacent ecosystems. To translate riparian ecosystem processes into policy, we define *riverine corridor systems* as networks of river channels, floodplains, and riparian areas that require lateral, vertical, and longitudinal connectivity from headwaters to mouth. Because riverine corridor systems are embedded within a human-impacted landscape, we treat them as social-ecological systems that are dynamic, nested, hierarchical, and flow across social boundaries (12). Within these systems of interdependent lands and waters, there is a clear, multi-dimensional misfit between ecological and social structures and processes.

Legal bridges to connectivity

Landscape connectivity depends upon the spatial arrangement of biophysical characteristics, so how can we map the capacity to move toward effective governance and management of riverine corridor systems? *Governance* refers to both formal government and informal "structures and processes by which societies share power" (13); it establishes the social framework within which management must operate. Although adaptive management involves experimentation and feedback, it alone is not capable of coordinating piecemeal efforts, promoting social learning, or bridging discontinuities across boundaries. *Networked governance* can provide a framework for experimentation and dissemination of knowledge as well as the capacity of a social-ecological system to adapt or transform in response to disturbance (14, 15).

The first step in navigating governance for conservation is to identify the actors (16). Social values can be mapped to inform conservation planning (17) and land use and ownership maps reveal areas where corridors might be more politically feasible to establish and maintain (3). These maps display existing categorical information (e.g., public versus private lands), but do not quantify that information to make it compatible with other quantitative spatial datasets. Thus, habitat connectivity models do not formally incorporate spatially-explicit patterns in governmental authority through regulations, land use, and management or ownership across jurisdictional and property boundaries (Panel 1). To address this gap, we asked: *what sources of authority affect actions upon riverine lands? How is this authority configured spatially across a given landscape, and how might spatial patterns in legal authority inform landscape-scale conservation efforts?*

Our objective is to analyze the spatial arrangement of legal authority over lands within a riverine corridor system, highlighting opportunities to build capacity for cross-boundary coordination of governance for multiple conservation goals. We formulate a method to map multiple levels of government authority over the landscape at the local scale where the checkerboard nature of private land ownership imposes significant barriers to connectivity of land and water resource management. We present a reproducible method for assigning relative cost values to an authority landscape to represent the emergent role of accumulated layers of authority in promoting coordination across property boundaries. Finally, by integrating authority values with habitat corridor values in cost maps to generate a resistance surface for corridor analysis, we show how spatial relationships between landscape-scale conservation priorities and local patterns of authority over public and private lands can be used to inform conservation actions.

Methods

In a single, large county in Washington State (northwestern United States (U.S.)) that spans a habitat connectivity gap (Figure 1a), we mapped sources of authority over riverine lands. We focused on formal government and tribal nations as a subset of a governance system that also includes the public, private interest groups, and bridging organizations (e.g., The Nature Conservancy) (18). We assigned a conservation authority index (CAI) value to each source of legal authority based on its scope and propensity to support conservation actions continuously across riverine lands (Panel 1) and summed the CAI by pixel (98x98 meters). Second, to spatially examine the multi-level legal landscape within the context of building habitat connectivity, we intersected a national-scale map of ecological corridor value with the sum of CAI values from our countywide authority map. We ranked, inverted, and combined these two sets of conservation values to quantify the combined legal and ecological frictional costs of movement (resistance) across the county. We envision the map products as resistance surfaces to quantify spatial patterns of legal-ecological bridges and barriers to rebuilding habitat connectivity.

Defining the social-ecological problem

Wildlife connectivity is a conservation target for multiple species across the Northwest (19). Core habitat in this region consists of protected areas (e.g., National Park, Wilderness Areas) enclosed by multiple-use public lands. These government-owned lands are subject to a patchwork of federal and state jurisdiction and management, while the surrounding lands are divided into private parcels under local or tribal land use regulations. This fragmented authority landscape inhibits the geographic continuity of riverine land conservation, limiting the provision of ecosystem services and co-benefits related to water resources, aquatic habitat, and species persistence. We selected Okanogan County to delineate our geographic information system (GIS) because it contains core habitat, public multiple-use lands, tribal lands, and a checkerboard of private parcels presenting barriers to landscape connectivity (Figure 1b).

Mapping conservation authority

To restrict GIS analysis to riverine corridors, we created a buffer proportional to stream size by multiplying the Strahler stream order (20) by 200 feet (~60 meters). We compiled the federal and state sources of authority over lands within this buffer under the federal Endangered Species Act and Clean Water Act as well as other applicable state laws, tribal code, and local government zoning. We reviewed the pertinent statutes, regulations, rules, and plans, collated available GIS data, and mapped the spatial extent of each source of authority (Table 1). For each source, we attributed polygons with the statutory and regulatory bases of authority, levels of government, agencies and other entities involved in implementation. We generated a raster map for each source of authority at sufficient resolution (98x98 meters) to capture the patterns of fragmentation and align with available ecological datasets without being unnecessarily computationally intensive.

Mapping the legal-ecological landscape

Connectivity modeling through least-cost analysis calculates the accumulative cost of movement across a resistance surface based upon the best available ecologically relevant spatial datasets (6). To generate a legal-ecological resistance surface, we needed a conservation authority value raster compatible with ecological measures of corridor value. We assigned a conservation authority index (CAI) value to each source of authority based on its role in providing geographically continuous governance for riverine land conservation (Panel 1; Table 1) and then summed the CAI values for all sources of authority by pixel (Figures 1c, 2). We then ranked the summed CAI values (1-10), such that the highest conservation authority had a value of 10.

To represent ecological corridor value, we utilized a map of national-scale high-value corridors (4), which was a composite of least-cost corridor outputs based on landscape naturalness as a proxy for accessibility by multiple species. We resampled and ranked the corridor model values (1-10) for the range of variability across the county, such that areas of higher ecological corridor value had higher rankings. We then inverted the conservation authority and ecological corridor rankings to transform them into cost maps, summed the two cost maps, and set all values outside riverine corridors to 1000 (very high cost) to create an integrated resistance surface (Figure 1d). Using core quality habitat (4) at opposite ends of the county as source areas, we calculated the least-cost corridor across the integrated resistance surface (Figure 3). To allow comparison between the national-scale ecological and local-scale authority corridor maps, we calculated zonal statistics by Reach Code (21). We then used nested conditional statements to categorize pairs of conservation authority and ecological corridor values by stream reach into four conservation categories across the county (Figure 4). All GIS analyses were completed in ArcGIS 10.5.

Results

Mapping conservation authority

The riverine conservation authority map (sum of CAI values, shown in Figures 1c, 2) illustrates spatial heterogeneity with areas of high value (sum of CAI >24) distributed across the county, crossing boundaries of land ownership and jurisdiction. Private riverine lands across Okanogan County displayed substantial variability in conservation authority over short distances, reflecting fragmentation by property boundaries (Figure 2). Within a given corridor, the conservation authority values were greatest and most continuous near stream banks. There was a break at the lateral extent of areas under stream-centered sources of authority (e.g., designated fish critical habitat or shoreline development restrictions); areas within the wider outer band of riverine corridors had lower conservation authority values and more complex spatial patterns.

Mapping the legal-ecological landscape

The integrated resistance surface (Figure 1d) showed low to moderate cost within riverine corridors where one or both input cost maps had low cost (i.e., high conservation value), as expected. A different cost pattern emerged when connectivity was incorporated by calculating least-cost conservation authority corridors across this resistance surface (Figure 3). Accumulative cost values ranged from < 6 million to 29 million for riverine corridor lands across the county. Low-cost conservation authority corridors generally covaried with areas of low to moderate authority cost and ecological corridor cost (i.e., moderate–high conservation values in both). However, two areas of high accumulative cost (potential barriers; circled in Figure 3) overlapped with areas of low to moderate cost in the integrated resistance surface that also had the highest national ecological corridor values. These riverine areas were characterized by fragmented jurisdiction, lack of designated critical habitat, and limited state-level shoreline jurisdiction.

We used conditional statements to group riverine conservation values into four categories (Figure 4). Areas where authority and ecological cost were both low were categorized as bridges (areas of conservation congruence); areas with both high authority and ecological costs were categorized as barriers. The intermediate areas, where authority and ecological costs diverged, distinguished places where either coordinated riparian restoration to improve habitat or changes in governance to address fragmentation of authority could present bridging opportunities for riverine corridor conservation.

Discussion

Mapping authority at the resolution of local government jurisdiction allows us to view spatially-explicit details of the legal-ecological landscape within the context of existing broader-scale maps for species conservation. This multi-scale, applicable approach may inform (1) landscape-scale conservation efforts and (2) local land use decision making within a broader spatial context by incorporating multiple conservation goals and aiming for system resilience through unpredictable change. Identifying conservation authority corridors is a first step toward mapping governance and emergent social capacity to coordinate conservation efforts across boundaries. Future steps may involve mapping the roles of bridging organizations, community-based social networks, or economic factors associated with land use. This type of spatially-explicit mapping to represent integrated, cross-scale social-ecological conservation landscapes can be readily adapted to other places and contexts in which a spatial misfit between ecological and social systems needs to be addressed.

Connectivity of governance: building capacity to manage for resilience

Riverine corridor network conservation in the U.S. exemplifies the need to build coordination capacity because existing governance systems struggle to support management befitting the multi-dimensional connectivity of riverine corridor systems, despite broad agreement that riverside lands should be conserved. U.S. riverine land governance is divided among multiple agencies and organizations ranging in scope from local to national. Each entity acts upon its own mission, goals, processes and timeframes within a scope delineated by property boundaries. As a result, the governance landscape in riverine corridor systems, as well as other terrestrial systems, is highly fragmented (22) (Figure 2).

Valuing and mapping legal authority in formats compatible with ecological connectivity analyses may help to counteract this fragmentation by revealing opportunities to build connectivity through further coordination, restoration, and/or policy change. For instance, low-cost ($<10 \times 10^6$) conservation authority corridors linked rivers and streams across drainage divides (Figure 3). In those locations, conserving riverine corridor connectivity beyond the extent of designated fish habitat could provide corridors for wildlife movement with co-benefits for water quality. Furthermore, different routes might be prioritized for building habitat connectivity when legal authority is included than when models rely upon ecological conditions alone, e.g., where conservation authority corridors diverged from areas of highest ecological corridor value. The legal-ecological maps in this study (Figures 1d, 3; 4) present one of many possible formulations to assess the relative costs of building connectivity along different corridors. Here, we limited our analyses to riverine corridors and emphasized conservation authority and habitat corridor values, but integrative resistance surfaces could be tailored to address many other conservation scenarios.

Building upon emergent seeds of adaptive governance could contribute to the long-term success of corridor conservation initiatives. In the case of riverine lands, strategic conservation for multi-dimensional connectivity has many co-benefits, which may incentivize coordination among government agencies and opportunities to leverage funding from multiple sources (7, 9). Place-based representation of conservation authority in a familiar map format that is compatible with other spatial datasets may help to foster new collaborations or prioritize local actions. The process of coordination itself builds social capacity for governance and may lay the groundwork for future adaptation or transformation in response to change.

Acknowledgements

We thank the State of Washington Water Research Center (Seed grant #130985-001).

References

1. Ceballos G, Ehrlich PR, Dirzo R (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proc Natl Acad Sci*:201704949.
2. Hilty JA, Merenlender AM, Lidicker WZ (2006) *Corridor Ecology: The science and practice of linking landscapes for biodiversity conservation* (Island Press).
3. Brodie JF, et al. (2016) Connecting science, policy, and implementation for landscape-scale habitat connectivity. *Conserv Biol* 30(5). doi:10.1111/cobi.12667.
4. Belote RT, et al. (2016) Identifying Corridors among Large Protected Areas in the United States. *PLoS One* 11(4):e0154223.
5. Fremier AK, et al. (2013) Understanding Spatiotemporal Lags in Ecosystem Services to Improve Incentives. *Bioscience* 63(6):472–482.
6. Cushman SA, et al. (2013) Biological corridors and connectivity. *Key Topics in Conservation Biology 2* doi:10.1002/9781118520178.ch21.
7. Boisjolie BA, Santelmann M V., Flitcroft RL, Duncan SL (2017) Legal ecotones: A comparative analysis of riparian policy protection in the Oregon Coast Range, USA. *J Environ Manage* 197:206–220.
8. Bonebrake TC, et al. (2017) Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science. *Biol Rev*. doi:10.1111/brv.12344.
9. Fremier AK, et al. (2015) A riparian conservation network for ecological resilience. *Biol Conserv* 191:29–37.
10. Jones KR, Watson JEM, Possingham HP, Klein CJ (2016) Incorporating climate change into spatial conservation prioritisation: A review. *Biol Conserv* 194:121–130.
11. Anderson BJ, et al. (2009) Spatial covariance between biodiversity and other ecosystem service priorities. *J Appl Ecol* 46(4):888–896.
12. Berkes F, Colding J, Folke C eds. (2003) *Navigating social–ecological systems: building resilience for complexity and change.* (Cambridge University Press, Cambridge, UK).
13. Lebel L, et al. (2006) Governance and the Capacity to Manage Resilience in Regional Social-Ecological Systems. *Ecol Soc* 11(1):art19.

14. Chaffin BC, Gosnell H, Cosens BA (2014) A Decade of Adaptive Governance Scholarship: Synthesis and Future Directions.

15. Scarlett L, McKinney M (2016) Connecting people and places: the emerging role of network governance in large landscape conservation. *Front Ecol Environ* 14(3):116–125.

16. Alexander SM, Andrachuk M, Armitage D (2016) Navigating governance networks for community-based conservation. *Front Ecol Environ* 14(3):155–164.

17. Lechner AM, Brown G, Raymond CM (2015) Modeling the impact of future development and public conservation orientation on landscape connectivity for conservation planning. *Landsc Ecol* 30(4):699–713.

18. Decaro D, Chaffin BC, Schlager E, Garmestani AS, Ruhl JB (2017) Legal and Institutional Foundations of Adaptive Environmental Governance. *Ecol Soc* 22(1):32.

19. Providing a Regional Connectivity Perspective to Local Connectivity Conservation Decisions in the British Columbia–Washington Transboundary Region: Okanagan-Kettle Subregion Connectivity Assessment (2016).

20. Strahler AN (1957) Quantitative analysis of watershed geomorphology. *Trans Am Geophys Union* 38(6):913.

21. U.S. Geological Survey. National Hydrography Geodatabase. Accessed through Washington State Department of Ecology (2013) Available at: https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS/GIS-data [Accessed June 16, 2017].

22. Brinson MM et al. (2002) *Riparian Areas: Functions and Strategies for Management* (National Academy of Sciences).

23. Washington's State Wildlife Action Plan: 2015 Update (2015) (Olympia, Washington).

24. U.S. Geological Survey, Gap Analysis Program. Protected Areas Database of the United States (PADUS), version 1.4 Combined Feature Class (2016) Available at: https://gapanalysis.usgs.gov/padus/ [Accessed November 29, 2016].

25. U.S. Geological Survey. National Elevation Dataset (NED) 1 arc-second (2013) Available at: https://nationalmap.gov/index.html [Accessed March 9, 2016].

26. Washington State Department of Ecology and Department of Natural Resources. Water Resource Inventory Areas (WRIA) (2011) Available at: https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS/GIS-data [Accessed July 12, 2017].

27. Washington State Department of Ecology GIS data. Total Maximum Daily Load (TMDL) Maps (2014) Available at: https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS/GIS-data [Accessed June 13, 2017].

28. Okanogan County GIS data. Conservation easements (2015) Available at: http://okanogancounty.org/planning/data.htm [Accessed June 5, 2017].

29. NOAA Fisheries West Coast Region Endangered Species Act Critical Habitat: Critical Habitat for the Upper Columbia River Steelhead ESU (2005) Available at: http://www.westcoast.fisheries.noaa.gov/maps_data/endangered_species_act_critical_habitat.html [Accessed June 26, 2017].

30. U.S. Fish and Wildlife Service. Threatened and Endangered Species Active Critical Habitat Report (2014) Available at: https://ecos.fws.gov/ecp/report/table/critical-habitat.html [Accessed June 17, 2017].

31. U. S. Fish and Wildlife Service. National Wetlands Inventory Version 2.0 (2016) Available at: http://www.fws.gov/wetlands/ [Accessed July 10, 2017].

32. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Coastal Services Center and the Washington State Department of Ecology, Shorelands and Environmental Assistance Program. Wetlands Inventory 2011 (2013).

33. Washington State Department of Natural Resources. Forest Practices Wetlands (1995) Available at: http://data-wadnr.opendata.arcgis.com/datasets/forest-practices-wetlands [Accessed December 7, 2017].

34. Washington State Department of Natural Resources Forest Practices Division. Site Class (2001) Available at: http://data-wadnr.opendata.arcgis.com/datasets/site-class [Accessed December 7, 2017].

35. Okanogan County GIS data. Zoning (2016) Available at: http://okanogancounty.org/planning/data.htm [Accessed June 5, 2017].

36. Okanogan County GIS Data. Priority Habitats and Species (2005) Available at: http://okanogancounty.org/planning/data.htm [Accessed June 5, 2017].

37. Okanogan County GIS data. Current shorelines (2009) Available at: http://okanogancounty.org/planning/data.htm [Accessed June 5, 2017].

38. Washington State Department of Ecology, Shorelands and Environmental Assistance Program. SMA Jurisdiction Lakes (2017) Available at: https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS/GIS-data [Accessed April 19, 2017].

39. Washington State Department of Ecology, Shorelands and Environmental Assistance Program. SMA Jurisdiction Streams (2017) Available at: https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS/GIS-data [Accessed April 19, 2017].

40. Washington State Department of Ecology GIS data. Tribal Lands of Washington (2016) Available at: https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS/GIS-data [Accessed June 13, 2017].

41. Washington State Department of Natural Resources GIS data. Aquatic Parcel (2003) Available at: https://fortress.wa.gov/dnr/adminsa/gisdata/metadata/alo_aquatic_parcel.htm [Accessed June 30, 2017].

Figures with Legends

Figure 1. (a) Vegetation classification used in the Washington State Wildlife Action Plan (23). (b) Land ownership and management in Okanogan County, Washington. Hatched areas are managed for biodiversity; gray area is privately owned. Map layers were generated from existing data sources (24, 25). (c) Sum of conservation authority index (CAI) values (see Table 1) by pixel, displayed as maximum sum of CAI values per reach. See Figure 2 for pixel-level detail for inset area (gray box). (d) Integrated resistance surface. The conservation authority and ecological corridor value (4) maps were normalized, ranked and inverted to convert from value to cost before they were summed. (High values equate to low cost for both authority and naturalness.)

Figure 1(a)

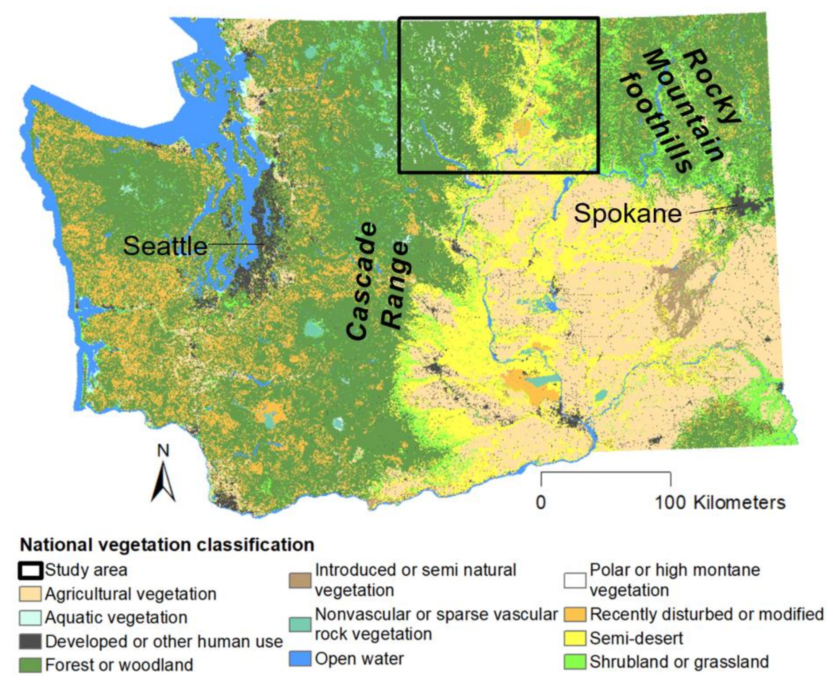


Figure 1(b)

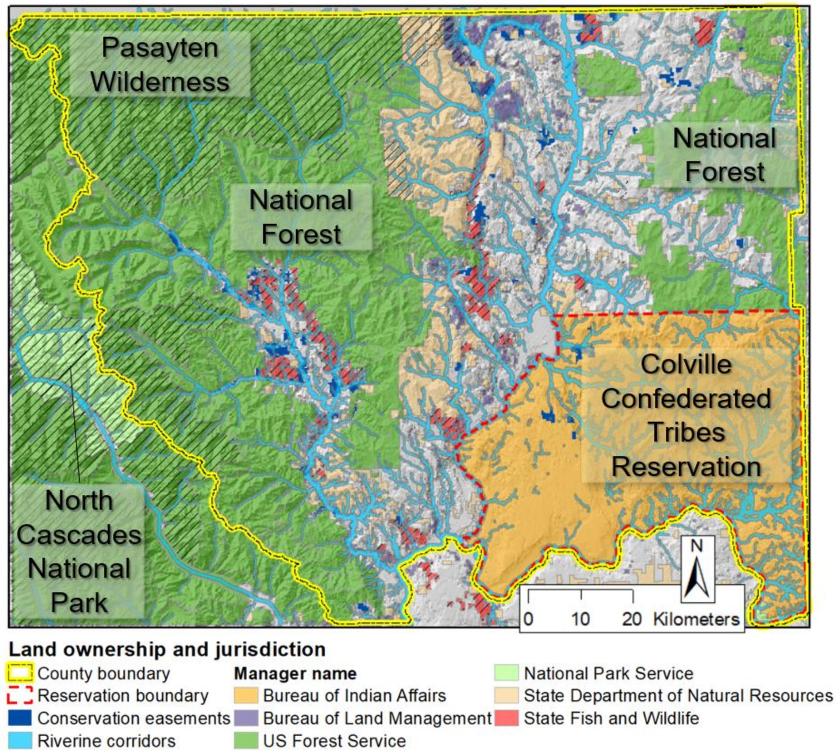


Figure 1(c)

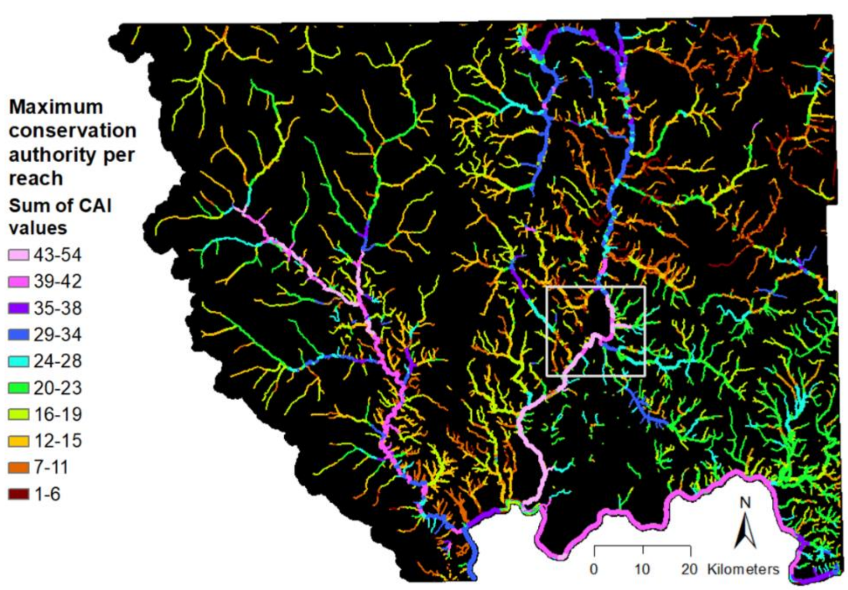


Figure 1(d)

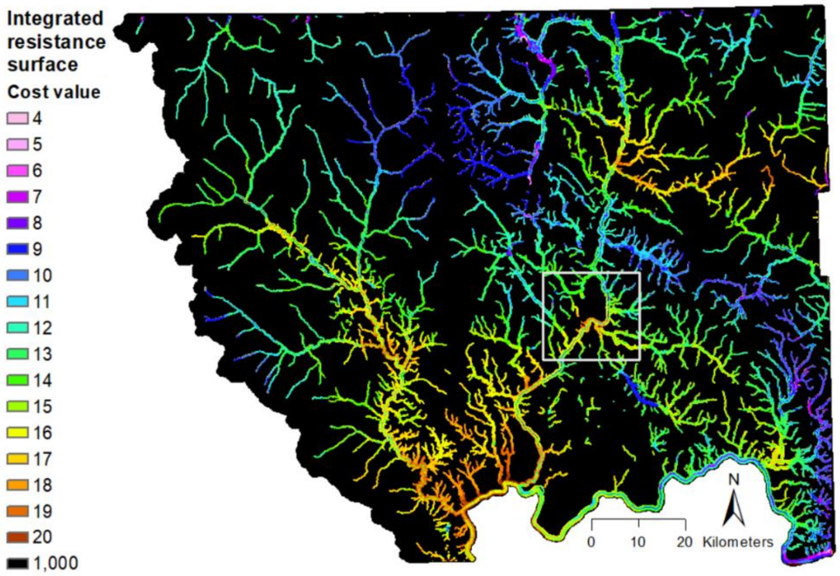


Figure 2. Finer-scale depiction of the spatial arrangement of conservation authority (sum of CAI values by pixel). Patterns in conservation authority reflect the fragmentation of the jurisdictional landscape by property boundaries.

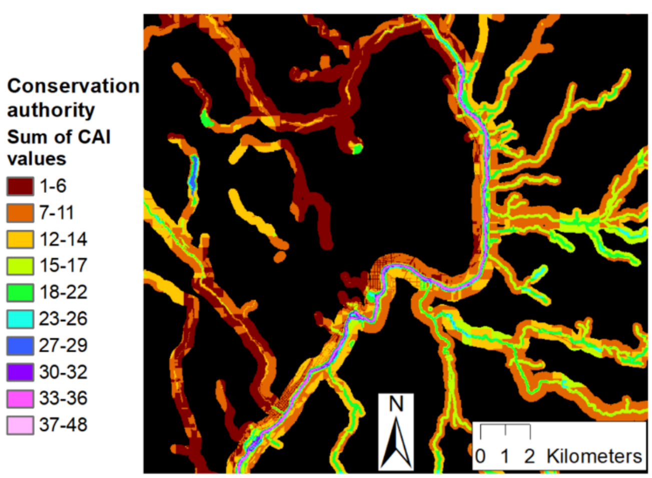


Figure 3. Least-cost conservation authority corridor output. Riverine corridor network boundaries are outlined in white. Transparent white overlay shows areas of highest habitat corridor value based on naturalness (4). Circles indicate areas where the habitat corridor value is highest, but the local riverine conservation authority corridor shows high cost due to fragmented jurisdiction, lack of designated critical habitat, and limited state-level shoreline jurisdiction. Alternatively, the legal-ecological analysis illustrates that other paths might be more efficiently connected by linking areas with overlapping layers of legal authority (see also Figure 4).

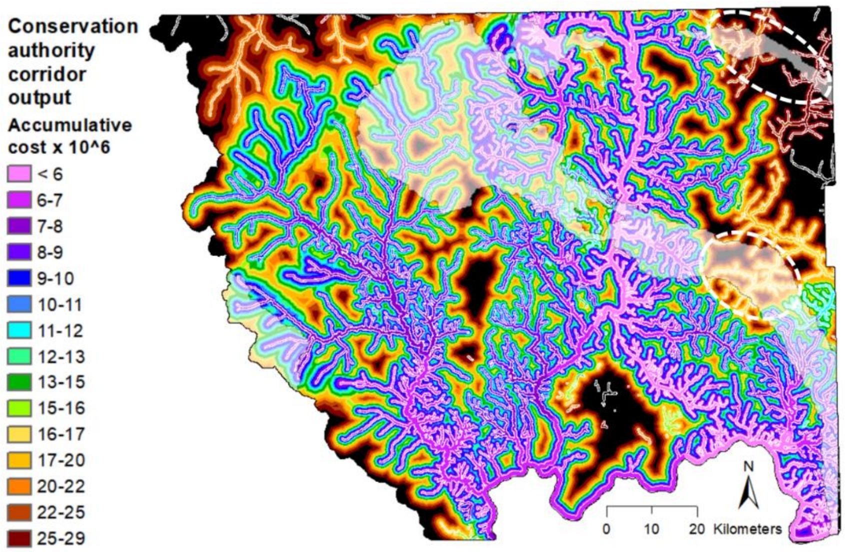


Figure 4. (a) Integrated legal-ecological assessment yields categories to inform conservation actions. (b) Same area as shown in Figure 2 for detail. Black and yellow riverine areas reflect moderate–poor landscape condition associated with cities, highways, privately-owned agricultural lands or semi-desert. In black riverine areas conservation authority values are also low; these are mainly private or tribal riverine lands fragmented by property boundaries. Yellow riverine areas indicate high conservation authority values and potential opportunities to build connectivity by improving riverine landscape condition. White and blue riverine areas have high corridor value, but blue areas may require additional coordination to build legal-ecological connectivity.

Figure 4(a).

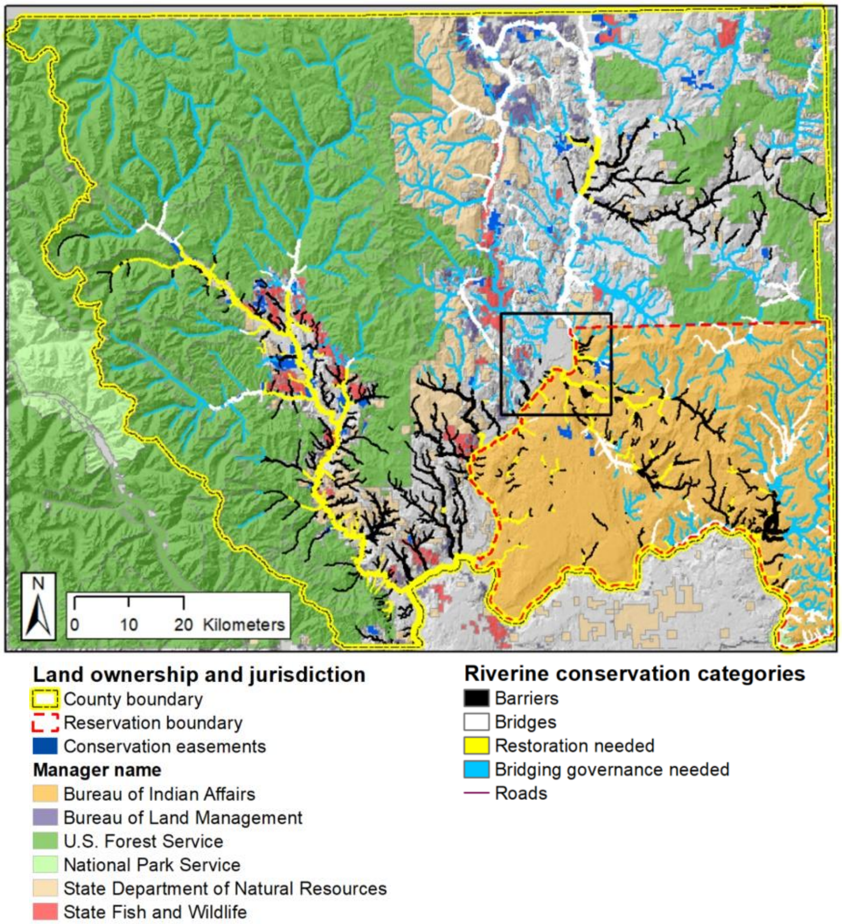
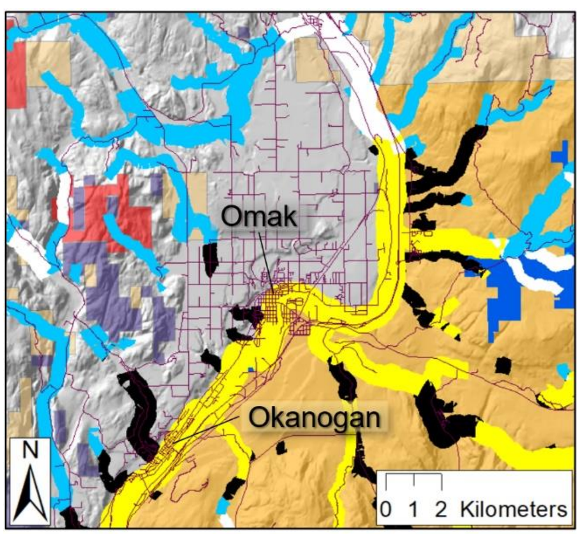


Figure 4(b).



Panel 1. Definitions of terms related to authority mapping.

Sources of authority: legal avenues of authority including (1) formal governmental authority through regulations, land use, or management and (2) ownership authority, which can be public or private. We attributed each mapped source of authority with its legal basis, agencies and organizations involved in implementation of associated actions on riverine lands.

Conservation authority index (CAI): value assigned to each source of authority that represents its relative influence on spatial connectivity of riverine land conservation actions. A higher CAI value indicates greater relative tendency to promote legal-ecological connectivity.

Conservation authority corridors: low-cost corridors revealed in a least-cost corridor output generated from an integrated legal-ecological resistance surface.

Table 1. Sources of authority mapped to riverine corridors for pilot study in Okanogan County, Washington (WA).

Source of authority	Primary agency	GIS data sources[1]	GIS input	CAI value[2]	Justification	Potential co-benefits of legal-ecological connectivity
CWA[3] Best Management Practices address **nonpoint source pollution** through TMDLs[4] or watershed (WRIA[5]) management plans	WA State Department of Ecology (Ecology)	Ecology GIS data (26, 27)	Clipped to riverine corridors	1	Coordinates voluntary riparian practices within a watershed	Increased effectiveness of pollutant removal
Conservation easements protect riverine lands by parcel	various	USGS[6] (24); Okanogan County GIS data (28)	Collated data and clipped to riverine corridors	2	May protect riverine lands across parcel boundaries	May provide opportunity for bridging organizations to implement ecological corridors, potentially increasing CAI value
ESA[7] protects **critical habitat** for *Oncorhynchus tshawytscha* (Spring Chinook salmon)	National Marine Fisheries Service (NOAA[8] Fisheries)	NOAA Fisheries ESA Critical Habitat GIS data (29)	Linear extent (polyline) extended laterally to ordinary high water mark	2	Protects riverine habitat longitudinally where adjacent uplands have fragmented jurisdiction	Promotes fish survival throughout life cycle
ESA protects **critical habitat** for *Salvelinus confluentus* (Bull trout)	U.S. Fish and Wildlife Service (FWS)	FWS Threatened and Endangered Species Active Critical Habitat Report (30)	Linear extent (polyline) extended laterally to ordinary high water mark	2		
ESA protects **critical habitat** for *Oncorhynchus mykiss* (Steelhead/rainbow trout)	National Marine Fisheries Service (NOAA Fisheries)	NOAA Fisheries ESA Critical Habitat GIS data (29)	Linear extent (polyline) extended laterally to ordinary high water mark	3	Protects riverine habitat longitudinally where adjacent uplands have fragmented jurisdiction, critical habitat bridges	

Source of authority	Primary agency	GIS data sources[1]	GIS input	CAI value[2]	Justification	Potential co-benefits of legal-ecological connectivity
					watershed boundaries	
CWA protects **wetlands** through reporting and permitting requirements	EPA[9], Ecology, USACE[10]	FWS, Ecology, DNR[11] GIS data (31–33)	Collated and merged available datasets. Clipped to riverine corridors for least-cost analysis.	3	Wetlands-based regulatory authority may be leveraged for multi-target corridor building	Increased likelihood of positive conservation outcomes if wetlands are linked to protected riverine corridors
Forest Practices' Riparian Management Rules protect water quality and fish habitat (balanced with timber extraction)	DNR	DNR GIS data (34)	Clipped to riverine corridors	3	May provide geographic continuity of riparian practices on state-owned forest lands, but there are a variety of approaches and corridor-scale connectivity is not necessarily intended	Increased likelihood of positive conservation outcomes if consistent riparian practices are extended beyond jurisdictional boundaries
ESA protects **critical habitat** for Canada lynx (*Lynx canadensis*) and Northern spotted owl (Strix occidentalis caurina)	FWS	FWS Threatened and Endangered Species Active Critical Habitat Report (30)	Clipped to riverine corridors	4	Protects habitat overlapping riverine lands, could be leveraged for multiple-goal corridors	Increased habitat connectivity may promote species persistence
Local or Tribal zoning authority may require set-backs on private lands	Local or Tribal government	Okanogan County GIS data (35)	Clipped to riverine corridors	4	Set-back zoning mandates protection on private lands	Increased likelihood of positive conservation outcomes with consistent set-backs across private lands
WA State Growth Management Act	WA State Department of Fish and Wildlife	WDFW Priority	Clipped to riverine corridors	5 for Riparian habitat; 4	Protects riparian habitat consistently statewide through	Framework for coordination among local governments

Source of authority	Primary agency	GIS data sources[1]	GIS input	CAI value[2]	Justification	Potential co-benefits of legal-ecological connectivity
mandates riparian habitat protection	(WDFW)	Habitats and Species (36)		for other habitats/ species	management or local policy guidance	receiving state-level policy guidance
Protected lands (GAP Status 1-3; see (24)) are managed by governmental agencies under applicable mandates	U.S. Forest Service, National Park Service, WDFW, DNR	USGS (24)	Queried and clipped to riverine corridors	5	Administrative practices can be consistent across large areas, but these vary among agencies, are limited to public land boundaries, and are subject to trade-offs, particularly on working lands	Increased likelihood of coordinated riparian habitat protection for water quality, biodiversity, and habitat connectivity, promoting ecological resilience
Local government shoreline master programs restrict privately owned shoreline development and use	County (local) government	Okanogan County GIS data (37)	Clipped to riverine corridors	5	Provides framework for continuity of legal protection along designated streams across a checkboard of privately owned parcels within a local government's jurisdictional area	Increased likelihood of positive conservation outcomes with consistent shoreline protection across property boundaries
WA State Shoreline Management Act (SMA) requires restrictions on shoreline development and land use for designated streams	Ecology	Ecology GIS data (38, 39)	Applied buffer to SMA-designated streams	6	Provides framework for continuity of legal protection along designated streams across the state	Increased likelihood of positive conservation outcomes with consistent shoreline protection statewide

Source of authority	Primary agency	GIS data sources[1]	GIS input	CAI value[2]	Justification	Potential co-benefits of legal-ecological connectivity
CCT[12] Shoreline Code restricts shoreline development and use	CCT Comprehensive Planning Department	USGS (21); Ecology GIS data (40)	Buffered streams and waterbodies within Reservation boundaries	6	Provides framework for protection of riverine lands throughout the Reservation	Increased likelihood of positive conservation outcomes with consistent riparian habitat protection across property boundaries
Government-owned aquatic parcels are managed by governmental agencies under applicable mandates	DNR	DNR GIS data (41)	Clipped to riverine corridors	6	Provides potential longitudinal continuity of practices for riverbanks where adjacent uplands have fragmented jurisdiction	Increased likelihood of coordinated riverbank management practices that could improve water quality and biodiversity

[1] All GIS data were publicly available online from government sources. These datasets were intended for agency use and public information. Disclaimers apply to any other uses of the data.
[2] CAI—Conservation authority index: value assigned to each source of authority that represents its relative influence on spatial connectivity of riverine land conservation actions. A higher CAI value indicates greater relative tendency to promote legal-ecological connectivity. Note that these values are specific to Washington and will vary by state and country, but the procedure is reproducible across scales and could incorporate data from surveys, social network modeling, or other sources.
[3] CWA—Clean Water Act
[4] TMDL—Total Maximum Daily Load (Clean Water Act)
[5] WRIA—Water Resource Inventory Area (specific to the State of Washington)
[6] USGS—U.S. Geological Survey
[7] ESA—Endangered Species Act
[8] NOAA—National Oceanic and Atmospheric Administration
[9] EPA—U.S. Environmental Protection Agency
[10] USACE—U.S. Army Corps of Engineers
[11] DNR—Washington State Department of Natural Resources
[12] CCT—Colville Confederated Tribes

Frequency Analysis of Historic and Future Droughts in Yakima Basin

Basic Information

Title:	Frequency Analysis of Historic and Future Droughts in Yakima Basin
Project Number:	2017WA429B
Start Date:	3/1/2017
End Date:	8/31/2018
Funding Source:	104B
Congressional District:	Washington
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Drought, Hydrology, Climatological Processes
Descriptors:	None
Principal Investigators:	yonas Demissie, Jennifer Adam, Akram Hossain

Publications

There are no publications.

Frequency Analysis of Historic and Future Droughts in the Yakima Basin
Interim Report
State of Washington Water Research Center
May 03, 2018

PI: Yonas Demissie

Abstract: A better characterization of droughts and their potential links to climate and hydrologic factors is essential for water resources planning and management in a drought-sensitive watershed like the Yakima Basin. Particularly, given the ongoing multi-agency efforts to adopt a complex and expensive water management plan for drought mitigation in the basin, detail study of the historical and future droughts plays a vital role in developing an effective plan. In this study, we proposed a comprehensive and probabilistic assessment of past and future droughts and their trends in the Yakima Basin using bivariate regional frequency analysis and Bayesian methodology. The study takes into consideration the proposed water management plan and impact of future climate and uncertainty. A new drought indicator is under development by combining drought indices from the total water supply, precipitation, snowpack, temperature, streamflow, and reservoir storage. The bivariate regional frequency analysis accounts the observed correlation between drought severity and duration in the region. The Bayesian statistics along with ensembles of future climate and hydrologic projections is used to quantify the uncertainty in the estimated return period, severity and duration of droughts. The effectiveness of the proposed water management plan in reducing the frequency and severity of droughts will be evaluated under various plausible climate projections. Besides providing much-needed insights about characteristics of droughts and their contributing factors, the outcome from the project is expected to have a direct contribution to the ongoing discussion of the effectiveness of the water management plan, and its benefit and cost analysis.

1. Hydroclimatological Conditions Responsible for Droughts in the Yakima Basin

In order to identify the underlying causes of droughts in the Yakima Basin, we have considered 11 historical droughts from 1947 to 2016 water years. Figure 1 shows those droughts and their level of severity, which are calculated using a new standard index based on the total water supply available (TWSA) in the basin. According to state legislation, drought emergency is declared when TWSA is below 75% of the long-term (1981-2005) average supply and causes a significant impact in the regional water users.

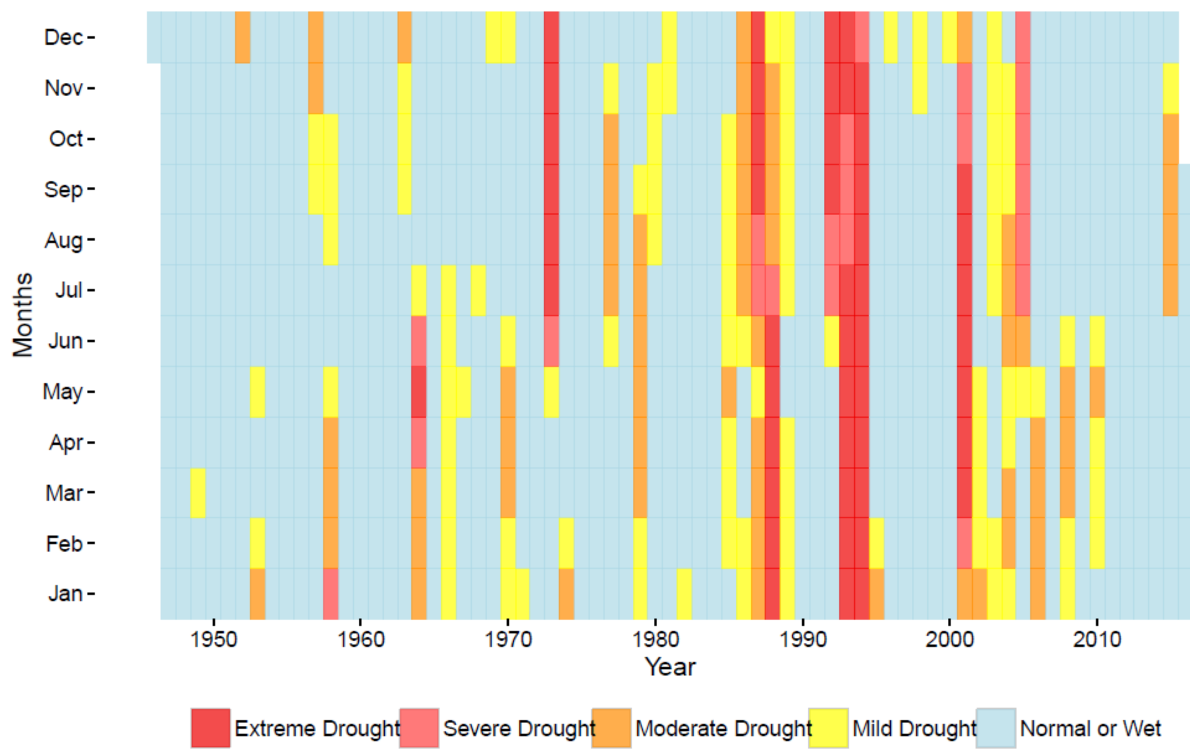


Figure 1. History of droughts and their severities in Yakima Basin

Various combinations of climate and hydrologic factors are responsible for the different drought conditions in the basin. For example, the carryover storage from the reservoirs plays an important role during both single and multiple year drought events. Despite record low snowfall, high winter and annual temperature and considerably below average annual rainfall the 2015 drought did not cause a major reduction in available water in the region. This could be attributed to reservoirs carryover from relatively wet 2014 year.

For this study, so far we have considered the following hydroclimatological factors: a) total amount of precipitation (PR), b) total snowfall within a water year (SN), c) average stream discharge within a water year (FL), d) average reservoirs storage within a water year (ST), e) carryover reservoir storage from the previous water year (CO), f) average winter maximum daily temperature (WT), and g) average spring maximum daily temperature (ST). Figure 2 shows the conditions of those factors during the 11 droughts in the basin. The percentile values for each factor are computed based on their 70 years (1947 – 2016) annual values. The lower percentiles for any given year indicates the potential shortage of the associated factor in that year. The x-axis in the figure represents drought years in descending order of severity. The 1994 drought is the most severe drought with the TWSA percentile being only 1.43, while the 1966 drought has 15.71 percentile. As shown in the figure the carryover storage from the previous year, which is just 1.4%, combined with relatively low precipitation (11.4%) and snowfall (28.6%) were the main causes of the significant reduction in streamflow and storage (1.4% both) and the severe drought in 1994. On the contrary, the 2001 drought, the next severe drought with TWSA of just 2.86% was mostly caused by the relatively small amount of precipitation (7.1%) the basin received that year. Otherwise, the snowfall and the carryover amounts are both near to their long-term average (50%) amounts. The next severe drought in the basin was the 1993 drought with TWSA of 4.28%. As shown in the figure, the snowfall was near record high (97.1%) and the rainfall (64.3) was well above the long-term average. Despite these large water input in the basin, the 1993 water year was one of the top severe droughts in the basin because of the relatively small carryover storage from the previous year (7.1%). A similar condition also attributes to the 1988 drought (5.71% TWSA), 2004 drought (10% TWSA). On the hand, the 1977 drought (14.28% TWSA) was caused by near to record low snowfall (7.1%) and rainfall (2.9), while the carryover storage from the previous year was well above average (87.1%).

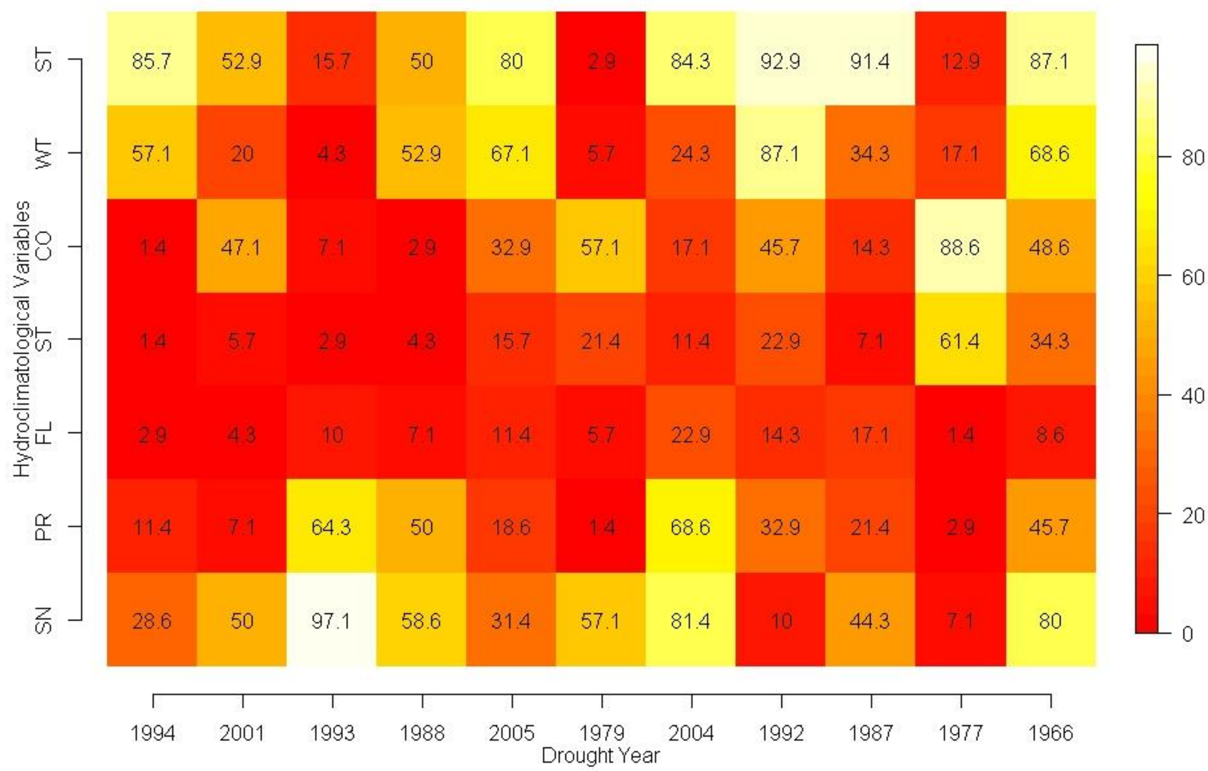


Figure 2. Past droughts in Yakima and the contributing hydroclimatological factors.

These preliminary findings highlight the different roles that the hydroclimatological conditions play in affecting drought and its severity in the Yakima Basin. Understanding these casual and physical relations among the different hydroclimatological conditions and droughts in the region will improve our ability to do a short-term and long-term forecast of the drought. In a related project, we are currently developing a deep learning approach for drought warning and forecast in the region. We have further examined the percentage changes in the TWSA, Yakima River discharge at the Parker station (USGS 12505000), spatially average precipitation, snowfall and temperature (Figure 3). The figure shows that on an average annual precipitation and snow can be reduced by 26% and 33% respectively along with 4% increase in annual average temperature during drought years. The average change in TWSA during drought years is approximately 55% with a maximum of 75% reduced TWSA in 1994 compared to the long-term average TWSA. Although there were high snow and precipitation in 1993, however, could not able to recover the drought condition caused by the 80% less snow during 1992. The results from this data analysis are currently in use to develop a new drought index. Unlike the traditional approaches, such as the standard precipitation index (SPI) and standardized runoff index (SRI), which use a single hydrology or climatology factor to identify and characterize droughts, the new drought index from this study combines the above factors to better characterize droughts in the region.

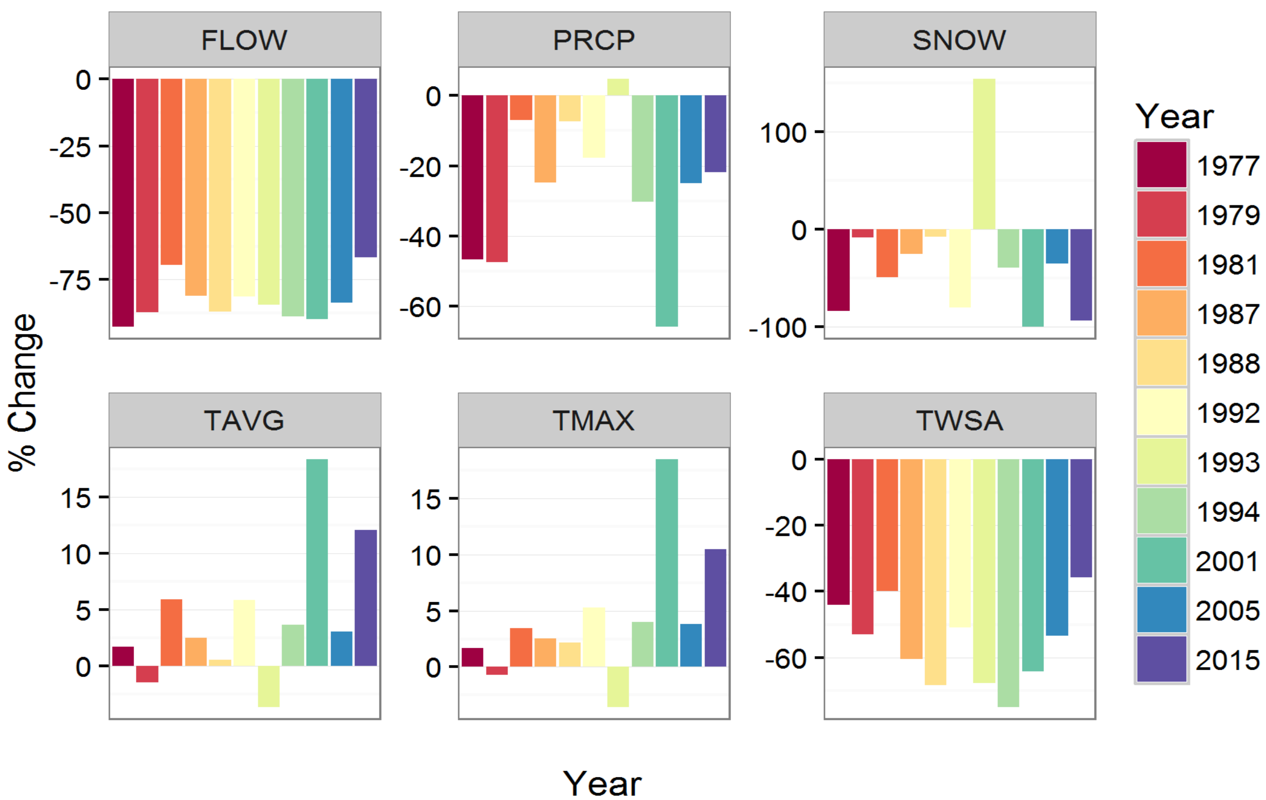


Figure 3. Change in the hydroclimatological conditions during different drought years compared to non-drought years

1. Trends in Hydroclimatological Factors

The Mann–Kendall statistics (Z) (Mann, 1945; Kendall, 1975), which uses the Z-test, was applied to investigate the presence of linear trend in total precipitation (PRCP) , rainfall(RAIN), average temperature (TAVG), maximum temperature (TMAX) and minimum temperature (TMIN). When$|Z| > Z_{crit}$, the null hypothesis of no trend can be rejected and the data is considered to have a significant trend. For the 95% confidence level, $Z_{crit} = 1.96$.

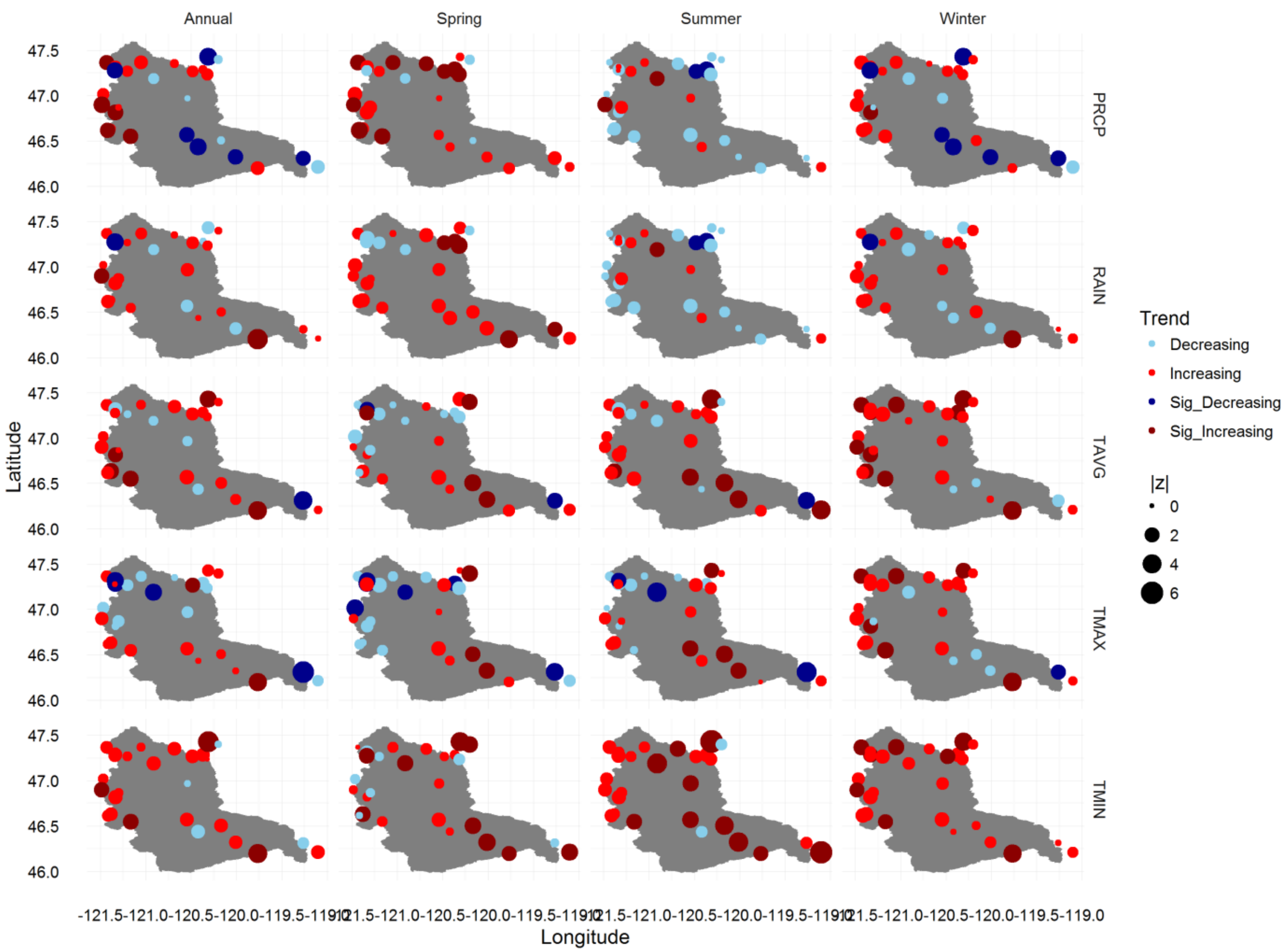
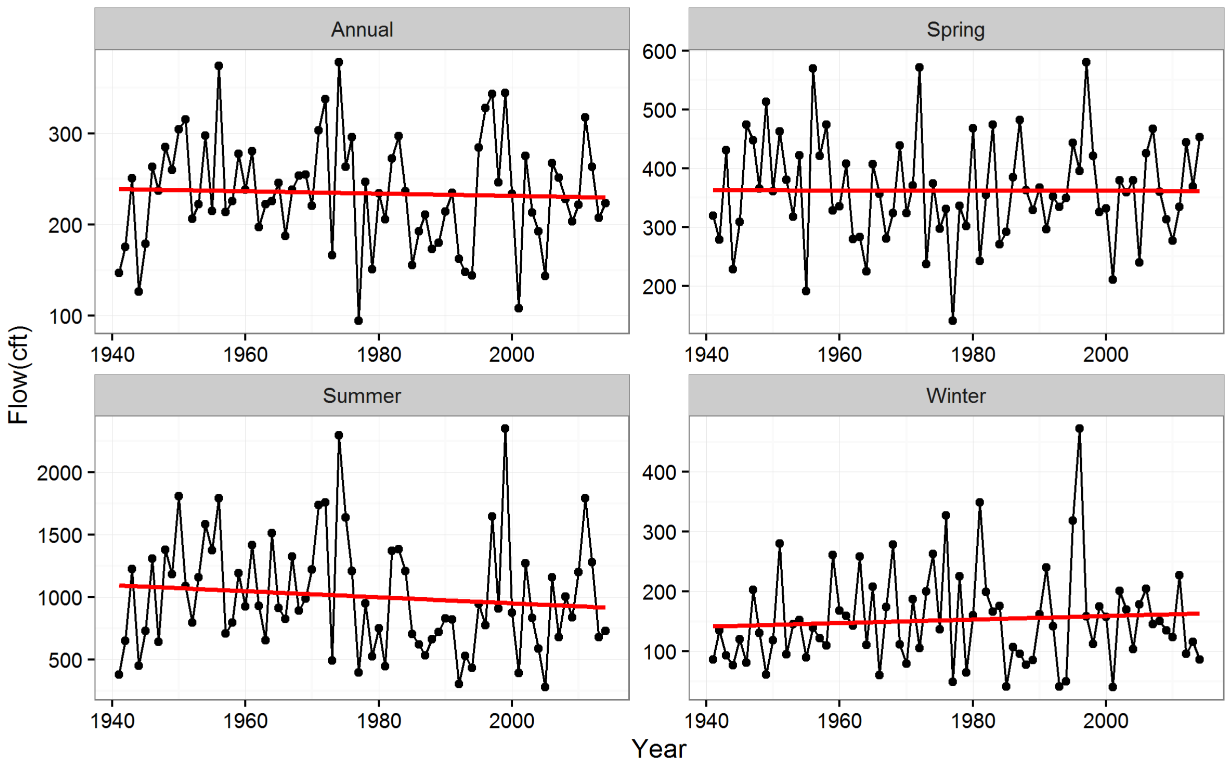


Figure 4. Spatial distribution of trend for the different Hydroclimatological factors.

At annual time scale, 72 % of the 29 stations showed increasing trend in rainfall out of which only two stations are statistically significant. On the other hand, 80% of the station showed increasing trend in average air temperature which primarily caused by the increase in minimum temperature. 83% of the stations shoed increasing trend in minimum temperature out of which 17% are significant. The spring(MAM) total precipitation showed an increasing trend in 86% of the stations out of which 36% are significant. On the other hand, for summer (JJA) precipitation 65% of the stations showed decreasing trend out of which only two stations are significant. Winter (DJF) average temperature showed an increase at 89% of the stations out of which 46 % are significant. This increasing trend in winter temperature resulted in increase of



rainfall during winter. 70 % of the station showed increasing trend in rainfall during winter.

Figure 5. Daily average streamflow for the USGS gage 12488500

Figure shows the temporal pattern of daily average stream flow for an undeveloped stream located on the upstream section of the basin. From the figure, it is apparent that there is an increase in Winter Flow and decrease in summer flow. Rise of winter air temperatures results in increase of rainfall as result a higher proportion of winter precipitation enters streams rather than being stored as snowpack.

2. Bivariate Regional Frequency Analysis of Droughts

A standardized index (SI) similar to SPI has been used to identify drought variables. The index uses total water supply instead of precipitation. *Drought duration* (*D*) has been identified as the number of consecutive intervals (months) where SI value is below -0.7, *Drought intensity* (*I*) is the average values of SI within a drought duration and *Drought Peak* (*P*) is the minimum value of SI within the drought duration.

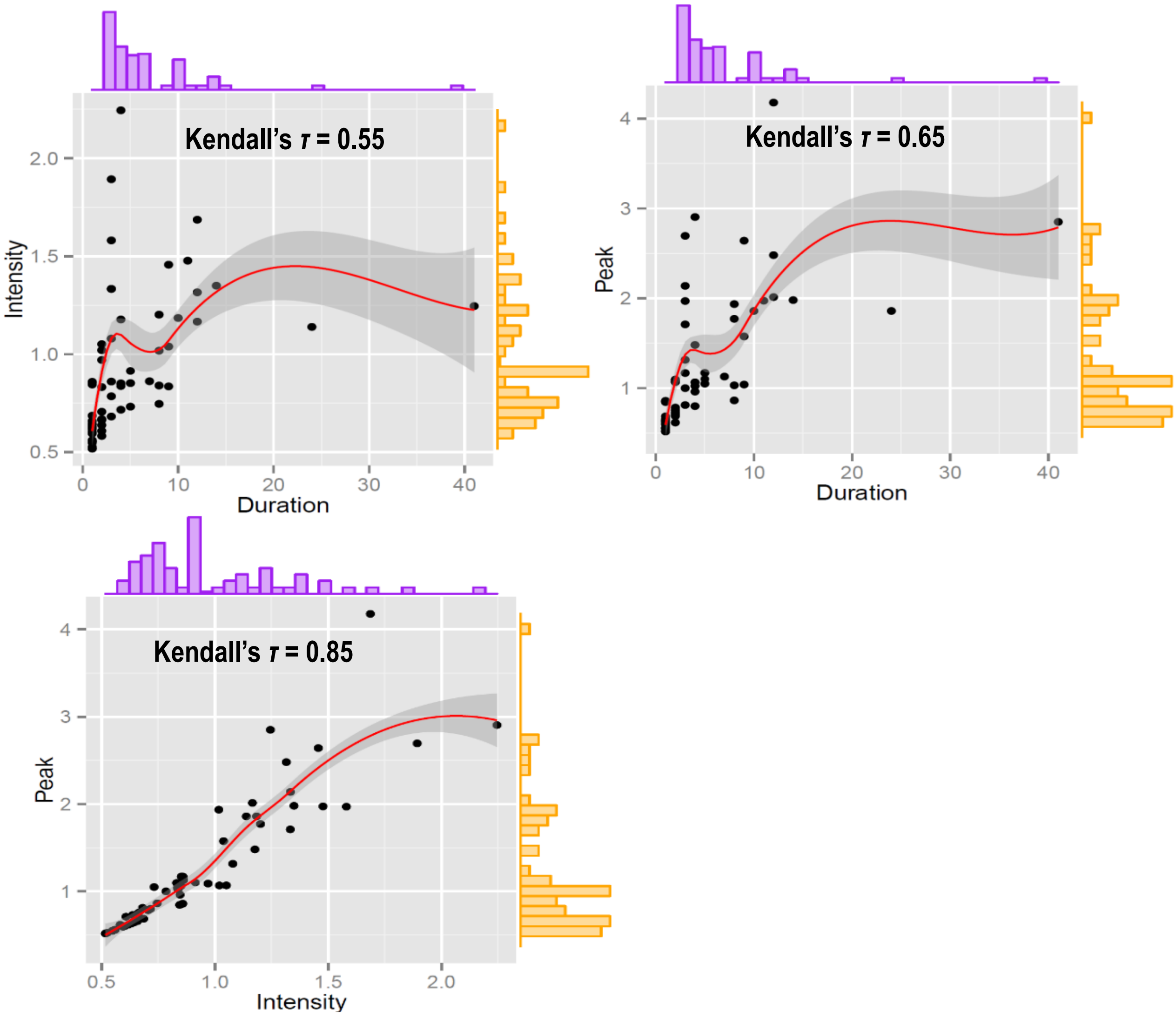


Figure 6. Correlation between drought durations, severities and peaks.

The dependence between drought variables were assessed using nonparametric Kendall's τ. The values of the Kendall's τ were found to be 0.55, 0.65 and 0.85 respectively for duration-intensity, duration-peak and intensity-peak indicating strong positive correlations among the variables in the basin. From the figure, it is apparent that the dependences are non-linear and as a result the joint probability of the two variables does not equal to their product, but should be modeled using some type of multivariate probability distribution. A three-parameter t-Copula function has been utilized to model drought variables and their correlations. Copula has the advantages over the traditional multivariate distributions in allowing usage of marginal distribution of any form and has ability to model nonlinear correlations between random variables irrespective of the marginal distributions (Salvadori and De Michele, 2004; Genest and Favre, 2007, Zhang and Singh 2007). Using the joint distribution obtained from the copula function, multivariate return period can be estimated. The multivariate return periods are best described using contour plots as there is no unique value of drought variables for a particular return period. Figure 7 shows the contour plot for Tand which represents the return period when both drought variables exceed their specified values and Tor which represents the return period when either drought variables exceed their specified values. Using this plot, one can estimate the frequency of occurrence of drought with specified combinations values of the drought variables. For example, a drought with duration of 10 months and intensity of 1.5 has a bivariate return period of 30 years for Tand and 10 years for Tor. Similarly, duration of 10 months and peak of 2.5 results in Tand of 25 years and Tor of 11 years.

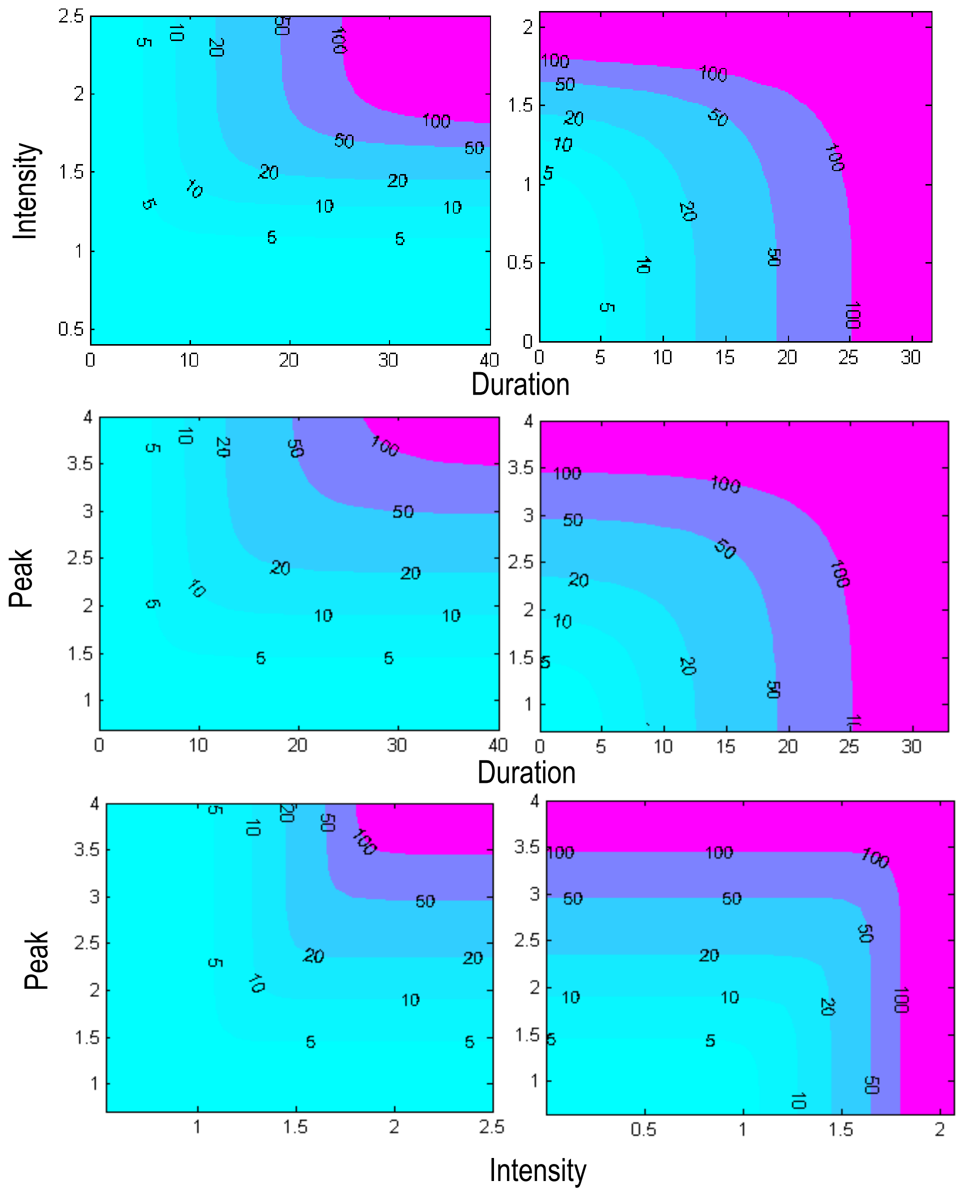


Figure 7. Contour plots of Bivariate return period of different drought variable combinations. The left panel is for Tor, while the right panel is Tand.

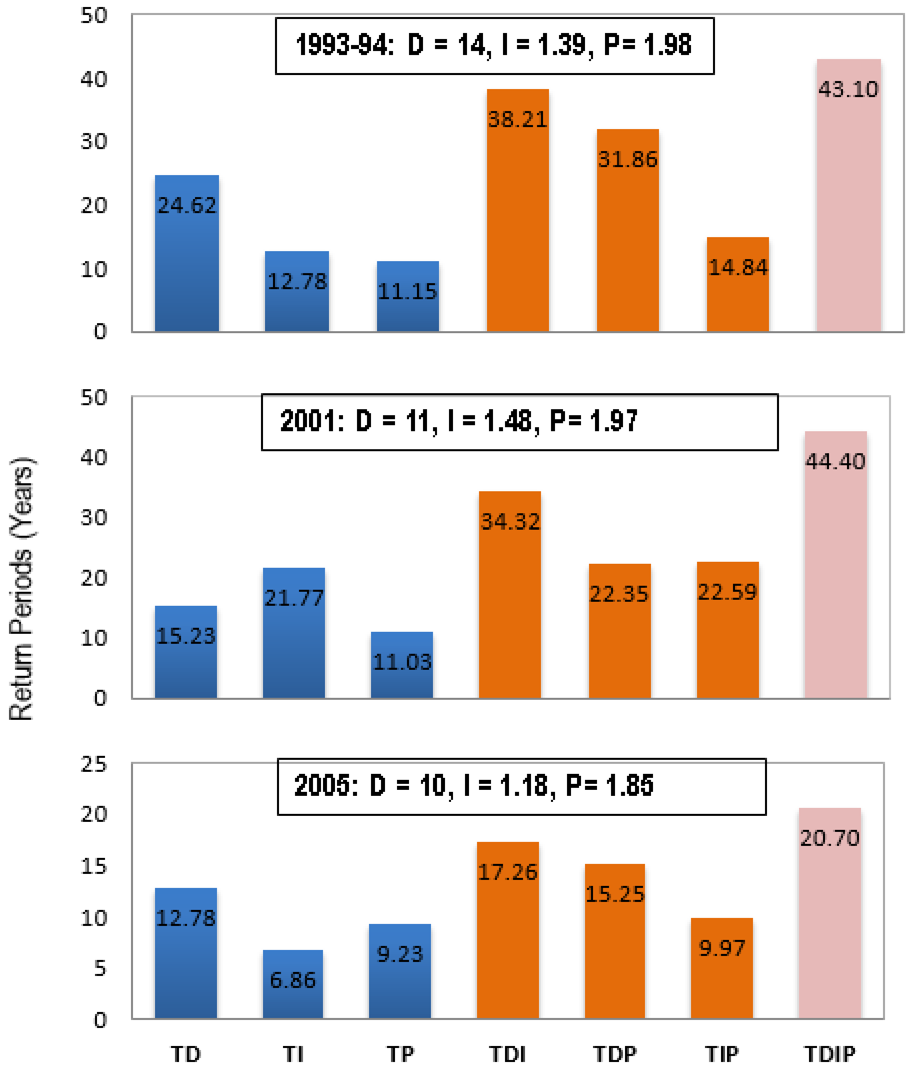


Figure 8. Comparison of univariate, bivariate and trivariate return periods for the three droughts. TD, TI and TP are return periods of the droughts durations, intensities and peaks, respectively, using a univariate analysis. TDI and TPI are the joint return periods (Tand) for duration and intensity and for peak and intensity, respectively. TDIP is the joint return period of duration, intensity and peak.

From Figure 8, it is apparent that the bivariate return periods Tand are higher than the univariate return periods but smaller than the trivariate return periods. On the other hand Tor is smallest for trivariate return period compared to the bivariate and univariate one (not shown). This highlight the importance of the multivariate frequency analysis to fully characterize the droughts return periods. The univariate return period can cause over/under estimation drought frequencies due to the existence of high correlation between drought variables.

Journal Articles and Presentations

- The preliminary results from this project was presented at the AGU Fall 2017 meeting (https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/280851).

Plan of work

Completed Tasks

- Data analysis to identify trends in the historical droughts
- Identification of the underlying hydrologic and climate conditions responsible for the historical droughts in the Yakima Basin.
- Developed the multivariate regional frequency analysis method
- Developed the Bayesian framework for quantifying uncertainty
- Preliminary application of the multivariate regional frequency analysis to characterize the historical droughts in the Yakima basin
- Presentation ate AGU Fall 2017 meeting.

Ongoing Tasks

- Analysis and integration of projected future climate and hydrologic data
- Developing a comprehensive drought index based on the combined effect of climate and hydrologic conditions that affect droughts in Yakima Basin.
- Evaluating the performance of the proposed water management plan in mitigating droughts under various future climate scenarios.
- A manuscript for Journal of Water Resources Planning and Management.

References

[1] Genest C, Favre AC (2007) Everything you always wanted to know about copula modelling but were afraid to ask. J Hydrol Eng 12(4):347–368. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:4(347)

[2] Genest C, Favre AC (2007) Everything you always wanted to know about copula modelling but were afraid to ask. J Hydrol Eng 12(4):347–368. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:4(347)

[3] Kendall MG (1975) Rank correlation measures. Charles Griffin, London

[4] Mann HB (1945) Non-parametric tests against trend. Econometrica 13(3):245–259. https://doi.org/10.2307/1907187

[5] Salvadori G, De Michele C (2004) Frequency analysis via copulas: theoretical aspects and applications to hydrological events. Water Resour Res 40(12):W12511. https://doi.org/10.1029/2004WR003133

[6] Zhang L, Singh VP (2007) Bivariate rainfall frequency distributions using Archimedean copulas. J Hydrol 332(1-2):93–109. https://doi.org/10.1016/j.jhydrol.2006.06.033

Information Transfer Program Introduction

Information Transfer Program Introduction

The WRC administration has been active in outreach with water research and management professionals, and other stakeholders in relation to both WRC research activities, and in response to requests by stakeholders on other pressing issues.

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2017WA430B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	Wa 5th
Research Category:	Not Applicable
Focus Categories:	None, None, None
Descriptors:	None
Principal Investigators:	Jonathan Yoder, Jennifer Adam

Publications

1. Aryal, Ballav, J. Yoder, R. G. Taylor Effects of Drought on Farm Revenues: Ten Western US States Annual Western Snow Conference April, 2017 Boise ID.
2. Padowski, Julie C. 2017. Water Resources Sustainability. ERSP 483- Guest Lecturer, 18 April, Pullman WA
3. Yoder, Jonathan. 2017. State of Washington Water Research Center Contributes to the debates over the Yakima Basin IWRM plan. National Institutes for Water Resources Meetings. Washington D.C., February.
4. Malek, K., J.C. Adam, C.O. Stockle, and T. Peters, 2017. Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses. Journal of Hydrology, doi: 10.1016/j.hydrol.2017.11.046
5. Padowski, Julie, Nigel Pickering, and Jonathan Yoder. 2017. Potential Groundwater Availability at the Hanford Site. Delivered to the Hanford Natural Resource Trustee Council as a contribution to the Trustee Council Groundwater Baseline Study. 24pp. October.
6. Padowski, J.C., Carrera, L. and Jawitz, J.W., 2016. Overcoming urban water insecurity with infrastructure and institutions. Water Res. Manage. 30(13), 4913-4926 doi:10.1007/s11269-016-1461-0
7. Yoder, Jonathan, Michael Brady, & Joseph Cook. 2016. Water markets and storage: Substitutes or complements for drought risk mitigation? Water Economics and Policy. http://www.worldscientific.com/doi/abs/10.1142/S2382624X16500053?src=recsys
8. Malek, Keyvan. 2017. Effects of Climate Change on Yakima River Basin Agriculture. Ph.D. Dissertation. WSU. 2010WA317A.

Publications by staff for WRC activities not included in Appendix

Barik,M., J.C. Adam, J. Yoder, M.P. Brady, D. Haller, M.E. Barber, Hall, S.A., C.E. Kruger, G.G. Yorgey, M. Downes, C.O. Stockle, B. Aryal, T. Carlson, G. Damiano, S. Dhungel, C. Einberger, K. Hamel-Reiken, M. Liu, K. Malek, S. McClure, R. Nelson, M. O'Brien, J. Padowski, K. Rajagopalan, Z. Rakib, B. Rushi, W. Valdez. 2017. 2016 Technical Supplement for the Columbia River Basin Long-Term Water Supply and Demand Forecast. Publication No. 16-12-008. Washington Department of Ecology, Olympia, WA. 216 pp. Available online at: [https://fortress.wa.gov/ecy/publications/SummaryPages/ 1612008.html](https://fortress.wa.gov/ecy/publications/SummaryPages/1612008.html) .

Barik, M.G., J.C. Adam, M.E. Barber, and B. Muhunthan, 2017. Improved landslide susceptibility prediction for sustainable forest management in an altered climate. Engineering Geology: doi:10.1016/j.enggeo.2017.09.026

Li, D., M.L. Wrzisien, M. Durand, J.C. Adam, and D.P. Lettenmaier, 2017. How much western United States streamflow originates as snow? Geophysical Research Letters, doi: 10.1002/2017GL073551.

Malek, K., C.O. Stöckle, R. Nelson, K.J. Chinnayakanahalli, Liu, M., Rajagopalan, K., Barik, M., and J. C. Adam, 2017. VIC-CropSyst: A regional-scale modeling platform to simulate the nexus of climate, hydrology, cropping systems, and human decisions, Geoscientific Model Development, doi: 10.5194/gmd-10-3059-2017.

Rajagopalan, K.R., K. Chinnayakanahalli, C.O. Stockle, R. Nelson, A. Hamlet, M. Brady, M. Barber, C. Kruger, K. Malek, G. Yorgey, S. Dinesh, and J.C. Adam, 2017, Impacts of near-term regional climate change on agricultural production in the Columbia River basin. Water Resources Research (in press)

Reyes, J.R., C. Tague, R.D. Evans, and J.C. Adam, 2017. Assessing the impact of parameter uncertainty on modeling grass biomass using a hybrid carbon allocation strategy. Journal of Advances in Modeling Earth Systems: doi: 10/1002/2017MS001022

Rose, V, Rollwagen-Bollens G, Bollens S. (2017) Interactive effects of phosphorus and zooplankton grazing on harmful algal blooms in a shallow temperate lake. Hydrobiologia 788: 345-359.

Yoder, Jonathan. In press 2018. Fiscal Gridlock over the water budget in Washington State: The politics and economics of pouring exempt wells into the Prior Appropriations bucket. Western Economics Forum.

2017 In preparation or review.

Garcia, E.S., C.L. Tague, J.C. Adam, and M.L. Liu, 2017. Resolution of climate data affects eco-hydrology model estimates more than redistribution of soil moisture in a western Oregon watershed, Ecological Modeling (submitted)

Khan, M.A., C.O. Stockle, T. Peters, J.C. Adam, R.G. Allen, R. Trezza, B. Lamb, and C. Jinshu, 2017. Evaluation of METRIC for estimation of actual evapotranspiration from dryland agricultural systems in eastern Washington State, Remote Sensing of Environment (in review)

Liu, M.L., J.C. Adam, Z. Zhu, and R. B. Myneni, 2017. Vegetation dynamics play a role in changing water fluxes over the conterminous U.S. during 1983-2009, J. Hydrology (submitted)

Malek, K., J.C. Adam, C.O. Stockle, and T. Peters, 2017. Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses. Journal of Hydrology (in review).

Malek, K., J.C. Adam, C. Stockle, M. Brady, K. Rajagopalan, 2018. When should irrigators invest in more water-efficient technologies as an adaptation to climate change? Water Resources Research (in review).

Shams, M., Guiney, L., Hersam, M., and Chowdhury, I. (2017) Influence of Functional Groups on the Degradation of Graphene under Direct Sunlight, in preparation for Environmental Science

Shams, M., Mansukhani, N., Henderson, W.M., Zepp, R., Bouchard, D., Hersam, M.C., Chowdhury, I. (2017) Environmental Implications of Two Dimensional Nanomaterials, in preparation (Invited Review to Environmental Science Nano)

Yang, Qingqing, Jonathan Yoder, and Michael Brady. In review. The value of including site metrics in meta-analysis for estimate transfer: Reducing generalization error in water demand estimation.

External organization involvement and service

Adam Jennifer 2016-2017. Project related meetings for Water Supply and Demand Forecast

Adam Jennifer 2016-2017. Workshops for BioEarth stakeholders

Adam Jennifer 2016-2017. WSU VCEA Dean Search: Advisory Committee Member

Adam Jennifer, Proposal Panel: NSF (2016), USDA (2017)

Adam Jennifer. Technical Documentation Reviewer: United States Bureau of Reclamation, Washington State Department of Ecology, Puget Sound Climate Science Synthesis.

Adam, Jennifer. 2012-17. Universities Council on Water Resources (UCOWR) 2016.

McCabe, Jacqueline 2017. Co-coordinator. INFEWS Kick-off meeting. Prosser WA., April 20-21.

McCabe, Jacqueline 2017. Co-coordinator. WSU-UI-OSU Tri-State FEW workshop. Coeur d'Alene ID, April 10-11.

Yoder, Jonathan 2015-2017. Universities Council on Water Resources (UCOWR) Board of Directors.

Yoder, Jonathan. 2015-2017. UCOWR Dissertation Award Committee. Chair 2017.

Yoder, Jonathan 2016-2017. Editorial board member, Journal of Water Economics and Policy.

Yoder, Jonathan. American Agricultural Economics Association Bruce Gardner Award for Policy Research Award Selection Committee 2017.

Yoder, Jonathan. 2/2017-3/2017 National Institutes for Water Resources (NIWR) Administrative meeting.

Yoder, Jonathan. April 2017. Reviewer, USGS 104G National Competitive Grant program, preproposal and proposal reviews. 2017.

Honors, awards and recognition by staff for WRC activities not included in Appendix

Marsh, Thomas, Jonathan Yoder, Tesfaye Deboche, Terry McElwain & Guy Palmer. 2016. Pastoralists' decisions on livestock vaccination translate into increased human capital and increased school attendance by girls. Science Advances: 2(12) e1601410, DOI: 10.1126/sciadv.1601410. Winner of the Western Agricultural Economics Association} Outstanding Published Research Award for 2017.

Yoder, Jonathan. 2017. 2016 Editors' Citation for Excellence in Refereeing - Water Resources Research [Journal].

Marisa Anne D'Angeli, Joe B. Baker, Douglas R. Call, Margaret A. Davis, Kelly J. Kauber, Uma Malhotra, Gregory T. Matsuura, Dale A. Moore, Chris Porter, Paul Pottinger, Virginia Stockwell, Carol Wagner, Ron Wohrle, Jonathan Yoder, Leah Hampson Yoke, Peter. 2016. Antimicrobial stewardship through a one health lens. 2017 Outstanding Paper Award for the International Journal of Health Governance.

Conferences Sponsored

2nd Tri-State Workshop for Food-Energy-Water Collaboration in the Pacific Northwest |23-24 October 2017| Oregon State University

- WRC Co-sponsor, co-organizer
- 29 participants

Tri-State FEW Workshop | 10-11 April 2017 | Coeur d'Alene, ID

- WRC co-sponsor, co-organizer
- 40 participants

Grant proposals submitted or in preparation

Optimizing Ground and Surface-Water Resources for Agricultural Production, Drinking Water Quality, and Ecosystem Health in Lower Umatilla Basin, Oregon. Agency, Oregon State University. Awarded, funding pending. 2017 ($310,025)

Bioretention Media Project. Agency, City of Pullman. Pending. 2017 ($18,000)

Western Water Spoke: A Big Data Synthesis and Delivery Framework for Coordinated and Timely Management of Surface Water and Groundwater Agency, New Mexico State University. Denied. 2017 ($141,725)

INFEWS/T3: Food, Energy, Water, Land and Social Stability (FEWLSS) in a Climate Constrained World. Agency, Carnegie Mellon University. Denied. 2017 ($599,351)

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	0	0	0	0	0
Masters	1	0	0	0	1
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	0	0
Total	3	0	0	0	3

Notable Awards and Achievements

Yoder, Jonathan. 2017. 2016 Editors' Citation for Excellence in Refereeing - Water Resources Research [Journal].

Rubayet Mortuza received the Ann Chittenden Holland Master's Thesis Award for Graduate Student Excellence for the 2016/17. [2015WA402B]

Publications from Prior Years

1. 2013WA374A ("Climate Change Effects on Water Supply: Linkages Between Wildfire and Accelerated Snowmelt") - Dissertations - Pracht, Lara E., University of Washington, ProQuest Dissertations Publishing, 2017. 10253449. Climate Change Effects on Water Supply: Linkages Between Wildfire and Accelerated Snowmelt. . 2013WA374A, 2015WA394B.